District and building level systems for optimised use of locally harvested renewable energy

Editor: Xingxing Zhang (HDA);

Contributors: Paolo Bonato (EURAC), Annamaria Belleri (EURAC), Chris Bales (HDA), Marco Lovati (HDA), Pei Huang (HDA), Puneet Kumar Saini (HDA), Tomas Sanchez De Soria (SOLARWALL), Sven Hallbeck (NIBE), Anders Becker (FERROAMP)

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Adaptable and adaptive RES envelope solutions to maximise energy harvesting and optimize EU building and district load matching

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List of abbreviations and acronyms

AC = Alternating Current
AHU = Air Handling Unit
API = Application Programing Interface
BYU = Bidirectional ventilation unit
COP = Coefficient of Performance
DC = Direct Current
DHW = Domestic Hot Water
DVU = Decentralized Ventilation Unit
ER = Exploitable result
EV = Electrical Vehicles
EXA = Exhausted air
HR = Heat recovery

HVAC = Heating Ventilation and Air Conditioning system
O&M = Operations & Maintenance
PV = Photovoltaics
SC = Self-Consumption
SWB = Solar window block
TRK = Trickle vents
UYU = Unidirectional ventilation unit

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Executive summary

This deliverable describes the main energy technologies and the possible systems for building and district in the Energy Matching project.

The first chapter reports technical information related to the **main technologies** as components included in Energy Matching project. The main results of the activities of the project focused on the single technologies, as well as design drivers and typical applications are reported for public readers.

In the following two chapters, the **overall system concepts** developed in the Energy Matching project are described. They are characterized into two categories: (1) heating & ventilation, and (2) renewable electricity generation. This part illustrates the main system concept, summarizes the main results of the activities of the project focused on system integration, and analyses the opportunities and barriers when matching among various energy sources.

In the last chapter, the **energy concepts designs** are demonstrated in three demo cases, respectively in Sweden, Italy and France. The associated energy performance of the coupled systems described in previous chapters are then evaluated and reported.

This deliverable covers four exploitable results[1] in Energy Matching project, which are useful information for the public to replicate the similar energy technologies at different levels. It includes energy concepts from the single component scale (e.g. Solar window package), to the building level (e.g. solar assisted air-source heat pump) to the multi-building or cluster scale (e.g. district DC nano-grid).

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[1] Energy Matching project exploitable results (ER) covered by this report:

- ER2 – EnergyMatching optimization tool;
- ER4 – Solar Window Package;
- ER6 – Renewable harvesting package to heat and ventilate;
- ER7 – Building and district energy harvesting management system

1. Energy Matching Technologies

1.1 Flexible, multi-source centralized heat pump unit

1.1.1 Description of the technology

Flexible, multi-source centralized heat pump unit is part of Energy Matching exploitable results 6 (ER6) – ‘Renewable harvesting package to heat and ventilate’ solution. Nibe has built up a modular heat pump framework that allows to exploit multiple heat sources using one or more interconnected heat pumps and/or compressors. The standard configuration (mostly used in small to medium size apartment buildings) has two heat pumps units that can be controlled independently or coupled in series/parallel and treated as a single unit. Of these two heat pumps, one operates with fixed speed and is controlled with an on/off logic, whereas the second can be frequency controlled. Thus, the whole system can provide a wide range of modulating heating rate. In the existing commercial units, this variable speed compressor derives its power from AC, with an AC/DC converter to first create DC power that can then be used to derive variable frequency compressor using an inverter. Within Energy Matching, it was possible to develop prototypes of heat pump that can use the DC-nanogrid from Ferroamp to power the variable speed compressor.

The heat pump units have an evaporator that can be connected via a brine or water loop to one or more heat sources. As long as an external loop is used, a large variety of sources can be connected. Standard heat sources are: exhaust air, with the use of a centralized heat exchanger that recovers waste heat; ambient air, with the use of an outdoor heat exchanger; ground source, with the use of a horizontal or vertical ground heat exchanger. At present, the product range has solutions in the range of 6 – 60 kW rated heating capacity. However, up to 8 such units can be cascaded and controlled by a single controller, so that the capacity range can be scaled up to 480 kW.

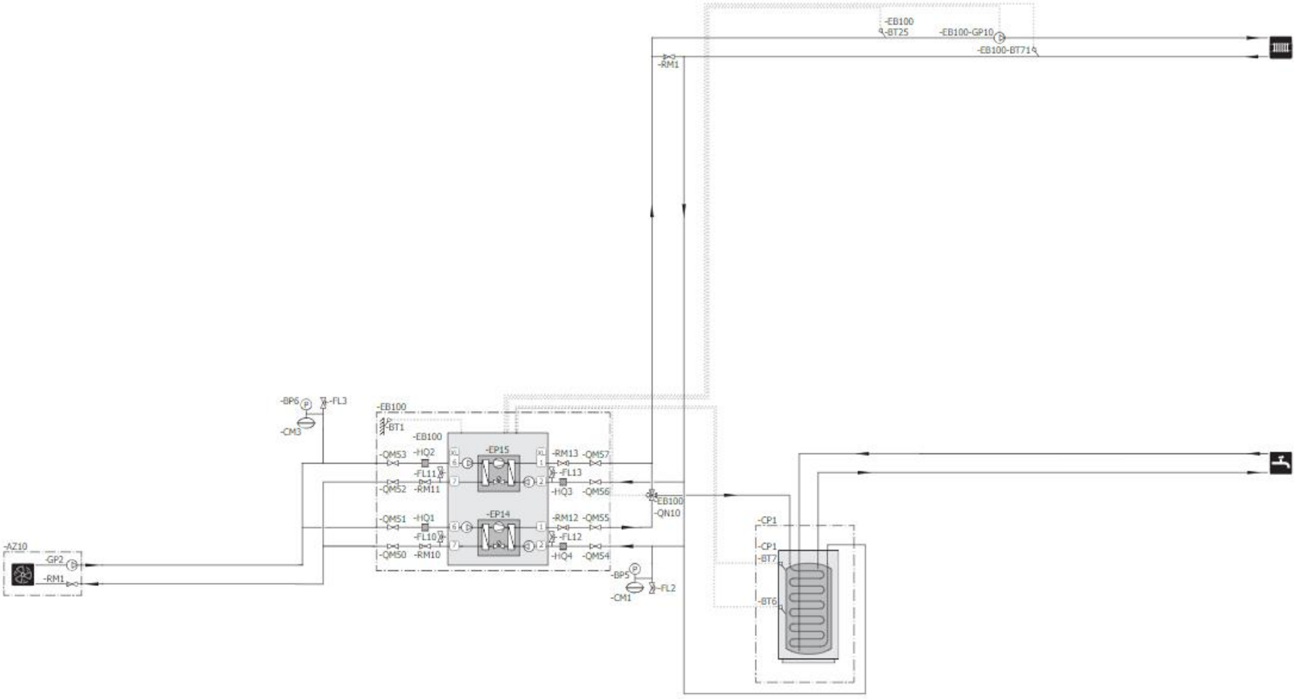

Figure 1. Simplest system based on exhaust air heat pump, as drawn by Nibe’s automatic design tool, with hot water and space heating (generated by Nibe automatic drawing tool)

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Additional heat sources as gas boilers, pellet boilers etc., can also be included in the final system configuration to complement the heat production of the heat pump for space heating and DHW preparation. Basic system schematics can be automatically generated using an open-access online design tool available on the website of Nibe (https://proffs.nibe.se/nibedocuments/25559/M11292-9.html), at present only in Swedish (English is only accessed by partners with login on www.nibe.eu). An English version can be accessed for Nibe partners with login rights. The user is guided in the selection of a range of options and, starting from that, the tool generates a standard schematic for the selected configuration, a list of required components and a short functional description. Figure 1. Simplest system based on exhaust air heat pump, as drawn by Nibe's automatic design tool, with hot water and space heating (generated by Nibe automatic drawing tool) shows a relatively simple system design, whereas Figure 2. Advanced system based on exhaust air heat pump, as drawn by Nibe's automatic design tool, with hot water, hot water circulation, space heating and cooling (active and passive). There are also a backup heater (EM1) and chiller (EP21) shows an advanced system design featuring cooling and external backup for both heating and cooling. Cooling can be provided either actively (via the heat pump), passively e.g. via ground heat exchanger, or with a backup chiller. These two figures are generated by Nibe automatic drawing tool. This highlights the flexibility the Nibe heat pumps have for different system concepts, which is integrated into the design process with this tool for generating system schematics automatically.

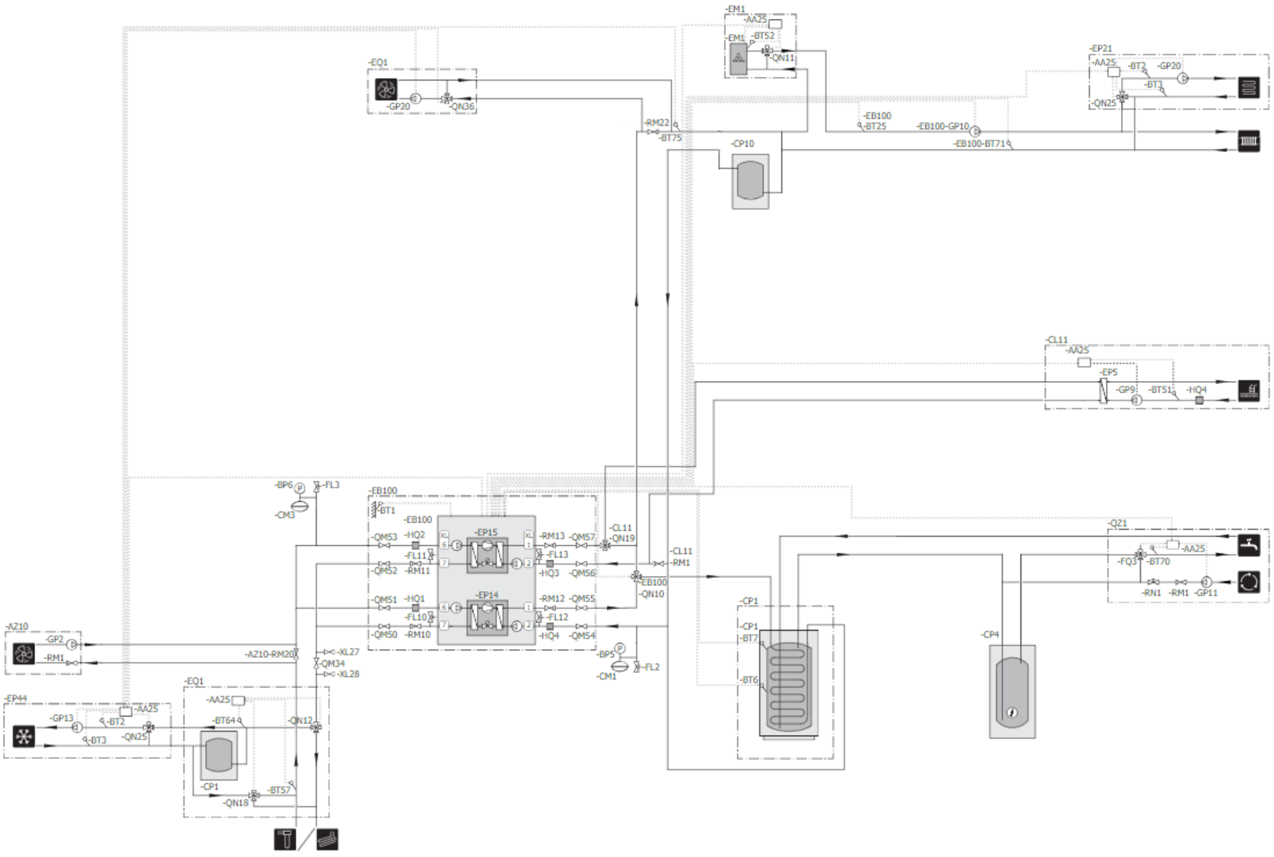

Figure 2. Advanced system based on exhaust air heat pump, as drawn by Nibe's automatic design tool, with hot water, hot water circulation, space heating and cooling (active and passive). There are also a backup heater (EM1) and chiller (EP21)

The modular design enables to accept a range of different renewable energy inputs at different times of the day/year, increasing the range of applicability and thus replicability. Based on this flexibility at different levels, various designs are proposed for the Italian demonstration building, one of which is shown in Figure 3. This variant is characterized by the generation of cooling power, the exploitation of multiple heat sources for the heat pump and the use of backup boiler for space heat and hot water.

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The main developments for Nibe within the Energy Matching project are: development of prototypes of heat pump integrating a variable speed compressor that can be fed directly by the Ferroamp DC-nanogrid; integration of additional sources (e.g. preheated air from SolarWall); development of advanced controls (Task 4.5 in WP4).

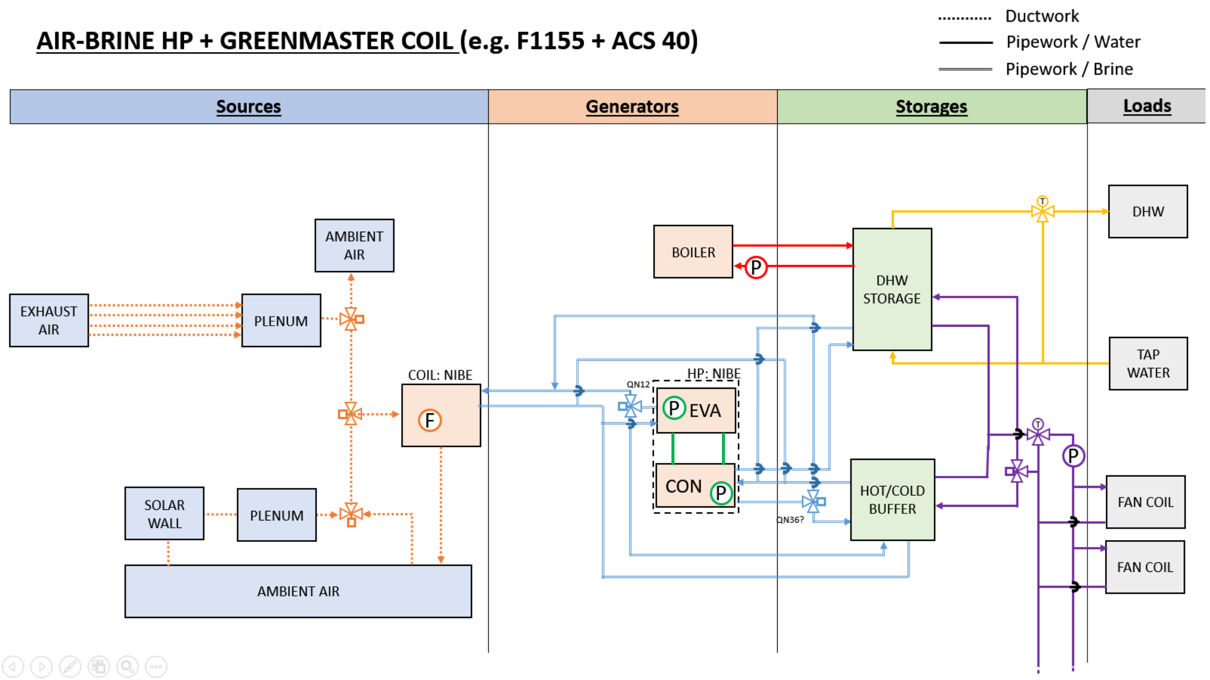

Figure 3. One of the proposed system variations discussed for the Italian demonstration building in Florence, with centralized hot water, heating and cooling together with multiple heat sources (in orange the aeraulic circuits, in blue the refrigerant circuit, in red the back-up circuit, in purple the heating/cooling loop and in yellow the DHW circuit)

1.1.2 Development and Test of Heat Pump Compressor connected to DC nanogrid

Figure 4 shows pictorially the working principle of how the DC coupled heat pump can be integrated with the Ferroamp DC nanogrid. NIBE has already designed and built a prototype heat pump, based on the commercial brine/water model F1255 (6 kW), that has a direct DC coupling with the Ferroamp DC nanogrid (part of ER7 - Building and district energy harvesting management system). This prototype was tested in-house at Nibe's own test facilities in Markeryd (Sweden), both before and after the modification to bypass the DC rectifier and connection to the 380 V DC input from a DC source. Testing was done according to the standard EN14511, and the results are shown in Table 1. The prototype has since been installed in a research house in the form of a test bed, so that it can be tested under realistic conditions for a longer period. The hardware and software used for this prototype is easy to adapt to other, larger models in the product range that have one or more compressors, and thus is easy to replicate to a wide range of system sizes and configuration.

Table 1. Results of the in-house testing of the DC-coupled and normal F1255 brine/water heat pump according to EN14511

	VB-Dt 5K	VB-Dt 8K	VB-Dt 5K	VB-Dt 8K	VB-Dt 5K	VB-Dt 8K	VB-Dt 5K	VB-Dt 8K
	30 Hz		**50 Hz**		**90 Hz**		**120 Hz**	
Brine in/Water out	**0/35'**	**0/55'**	**0/35'**	**0/55'**	**0/35'**	**0/55'**	**0/35'**	**0/55'**
Brine in °C	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Brine out °C	-3,0	-3,0	-3,0	-3,0	-3,0	-3,0	-3,0	-3,0
Water in °C	30,0	47,0	30,0	47,0	30,0	47,0	30,0	47,0
Water out °C	35,0	55,0	35,0	55,0	35,0	55,0	35,0	55,0
	DC	**DC**	**DC**	**DC**	**DC**	**DC**	**DC**	**DC**
Heat Capacity (kW)	1,810	1,426	3,053	2,616	5,964	5,283	8,029	7,379
	AC	**AC**	**AC**	**AC**	**AC**	**AC**	**AC**	**AC**
Heat Capacity (kW)	1,796	1,389	3,063	2,632	5,961	5,305	8,057	7,444

ΔCOP DC vs AC	3,4%	5,4%	1,9%	1,5%	1,9%	1,6%	1,6%	1,6%

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Figure 4. Illustration of how the DC coupled heat pump can be integrated with the Ferroamp DC nanogrid

1.1.3 Design drivers and typical applications

Compared to conventional heating and cooling systems (such as boiler, decentralized air conditioner), the main design drivers for this kind of centralized solution are lower investment and O&M costs from a holistic perspective, as well as high indoor air quality. However, an issue that can be faced passing from decentralized to centralized systems is the approval of the tenants.

Solution of this kind can be applied to nearly all buildings, even though they are particularly cost-effective in buildings that already have centralized heat and hot water distribution and/or exhaust air extraction. In this case, most of the infrastructure is already present and only a minimum amount of work is required in the building, and nearly all is done in the technical room. Previous projects in Sweden have shown that, if the infrastructure is already in place, a centralized system based on an exhaust air heat pump is more cost-effective than centralized heat recovery ventilation (Gustafsson et. Al, 2016), although no comparison was made with respect to decentralized solutions. With decentralized ventilation systems, it is however not always easy to ventilate the whole apartment without adding extra ducting, which can be both costly and invasive.

Another interesting advantage is the possibility to generate not only domestic hot water and space heating energy, but also -in some cases- also space cooling, further expanding the range of services provided.

From the energy perspective, if the building envelope is not very air-tight, recovering heat via heat pump is more effective than through ventilation heat recovery, since waste heat can be recovered also from air infiltrations.

1.2 Transpired solar thermal collector

1.2.1 Description of the technology

The SolarWall® air heating unit is part of ER6 – 'Renewable harvesting package to heat and ventilate' solution. It is a custom engineered solution containing many internal and external components, as shown in Figure 5. It uses solar energy to heat and ventilate indoor spaces in new and retrofit applications, as well as to heat air for manufacturing process and agricultural crop drying applications. The system design is optimized to maximize energy delivery with a minimum amount of static pressure in the airflow.

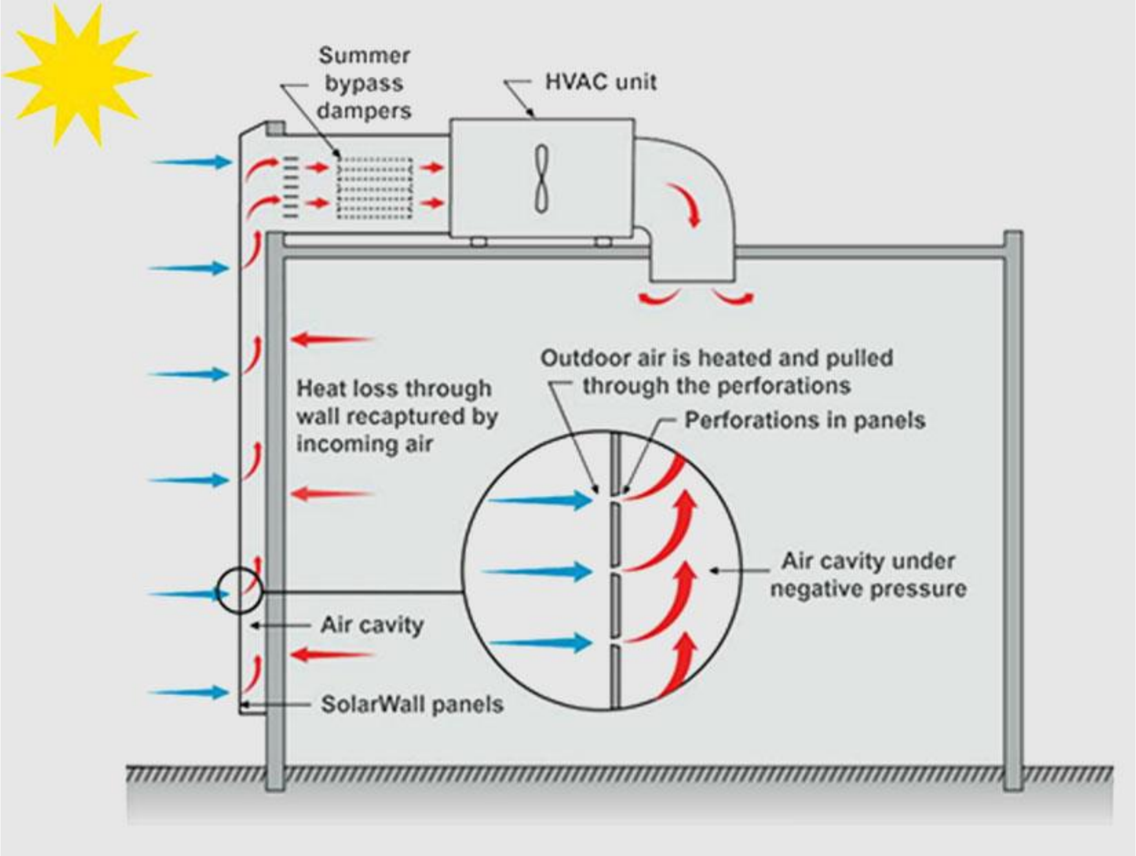


Figure 5. Concept drawing of a typical SolarWall installation

In order for the system to function, there must be an air-tight chamber achieved by separating the SolarWall panel from the existing wall using a sub-structure, also designed and manufactured by SolarWall. In order to close the chamber, continuous profiles are installed along its perimeter with trims that must conform to the existing wall and do exclude the passage of air. If necessary, it is also possible to seal with silicone or similar systems. If the insulation of the building is rigid, it is possible to use it as perimeter of the chamber, as long as the air-tightness is guaranteed and it is possible to anchor the edge profiles.

1.2.2 Main results

In this project, two SolarWall prototypes have been developed and monitored in Guadalajara, Spain from October 2019 until March 2020, including 1) a small scale prototype (6 m^2) with 45° slope under 4 airflow ranges, and 2) medium scale prototype mounted on the roof of a small office building and connected to a AHU. The data includes air cavity temperature, AHU supply temperature and outlet weather conditions. Figure 6 illustrates the the influence of the wind on the thermal efficiency of SolarWall. The thermal efficiency decreases at higher speed of the outside wind, while it increases at higher airflow within the air cavity. Wind speed is an important location-specific parameter to consider when designing the installation of the SolarWall component. Figure 7 shows the temperature increase with respect to solar radiation and the influence of the wind for a design flow of 36m³/h-m² within the air cavity. Higher temperature rise was measured at lower wind speeds. From the test, it is seen that the influence of the wind is negligible when airflow within the air cavity is 180 m³/hr-m².

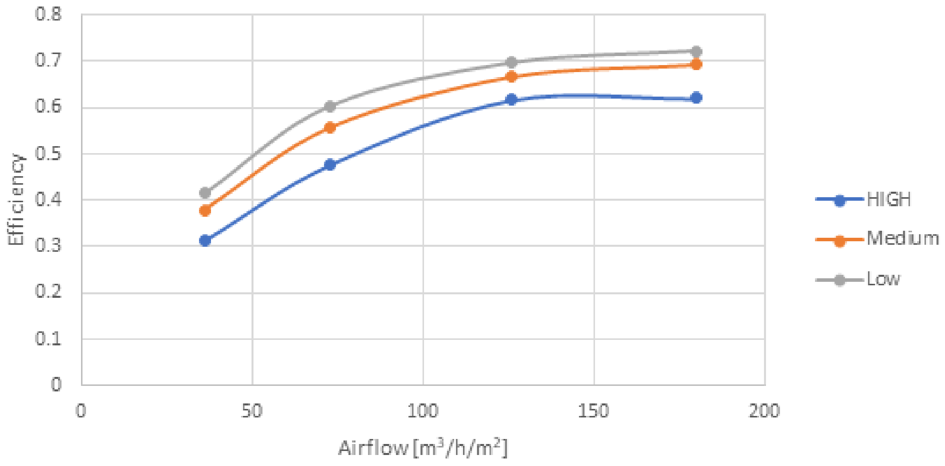


Figure 6. Thermal efficiency of solar wall depending on wind speed (high-medium-low).

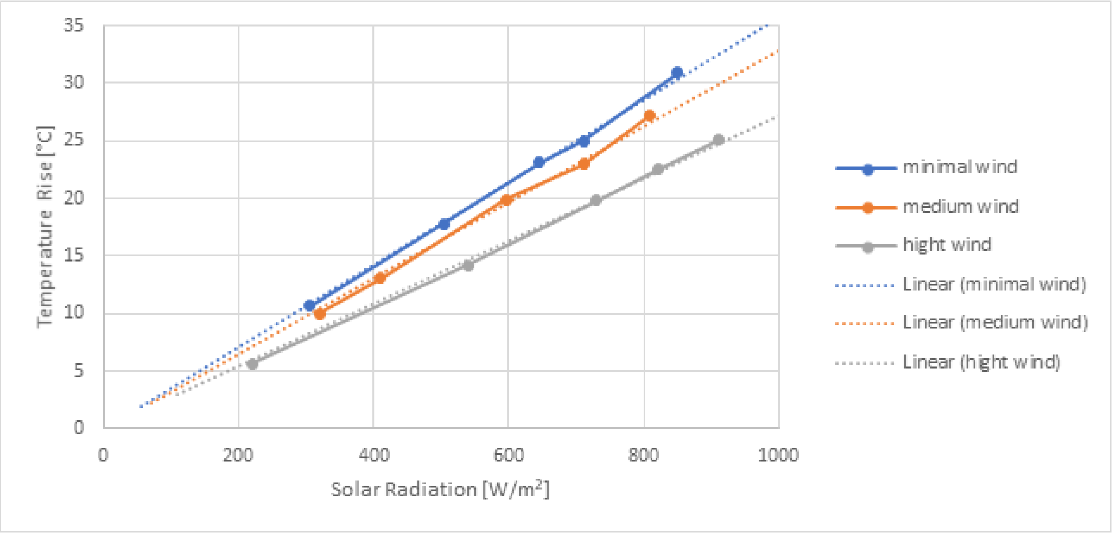


Figure 7. Temperature performance of SolarWall depending on incident solar radiation and wind speed at a fan driven airflow of 36 m³/hr/m².

1.2.3 Design drivers and typical applications

The metal panels are perforated with very small holes or slits and resemble a conventional metal facade. The panels are available in many colours including black, dark shades of brown, grey, red, blue and green. The panels are usually one meter wide and partially overlap to give a continuous appearance along the entire wall. To add structural strength and rigidity, the material is processed through rollers to form corrugations. The corrugations are 35 or 39 mm high and are spaced approximately 200 mm apart.

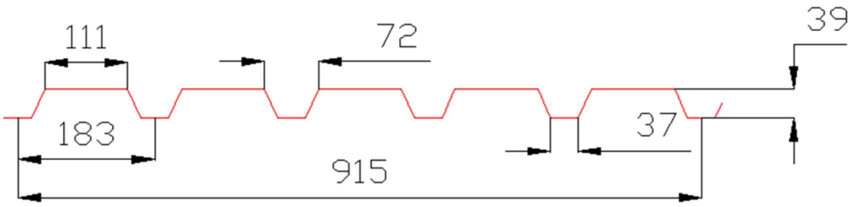


Figure 8. Main characteristics of the metal perforated plate (SolarWall source group company)

The dimensions and characteristics of the perforated panel collector can vary depending on design requirements and needs of each installation. These changes are subject to the supervision and sizing of Solarwall engineers, who collect information about required airflow and temperature swings (among other variables) to design the transpired solar collector and the others components of the SolarWall system. The galvanization protects the steel from rusting and the air movement through the holes dries any moisture that may exist. As the wall is generally vertical, water runs off the wall and the holes are so small that the surface tension prevents most water from entering the holes. The panels have a coating that guarantees a high solar absorptivity and a great durability to weather conditions (avoiding corrosion, scratching, etc).

A certain air gap is necessary to allow the heated air to travel up the wall and reach the nearest fan intake through a connection duct. The air gap and the size of the canopy can be reduced if the airflow is drawn off from more locations. The design of wall and canopy is based on three factors, that are volumetric airflow rate, cost and appearance. The cost and appearance issues are related, as a canopy is more expensive than a flat wall but it can also enhance the appearance of the building. If an internal canopy utilized, construction costs will be lower. The air space within the cladding profile may be sufficient for low flow designs but not sufficient for higher air volumes. If more air space is needed, the solar panel must be mounted further from the main wall. The method of securing the panel out from the wall will vary depending on the option selected.

The sub-structure is designed according to the characteristics of the installation, depending on parameters such as airflow, temperature ranges, morphology of the surface to install, availability of anchor points, dimensions of the airtight chamber, weather conditions, etc. Omega profiles are normally used in standard installations, as shown in the image below.

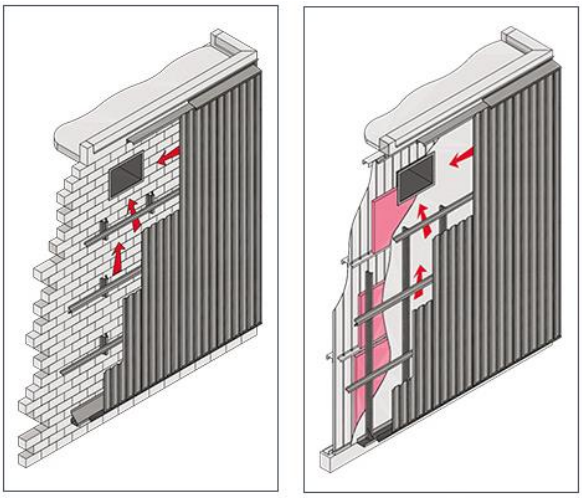


Figure 9. On the left, SolarWall panels on typical block wall construction. On the right, SolarWall panels on typical metal wall construction.

The system preheats the air that is introduced into the system through fans, which create a depression in the solar conduit. Concerning typical uses, SolarWall finds applications in:

Industrial sector: In many industrial processes, warm air is used for many different purposes, as seed drying, paint drying, etc. The incorporation of solar energy in a drying operation produces a double benefit in terms of improving both the drying process and the final product. SolarWall technology can heat large volumes of incoming air up to 55 °C above the environment, making it perfect for many crop drying applications. In a conventional active drying system, the SolarWall component can act as the main heating source during the day or in a preheating capacity, depending on the temperature required. SolarWall systems can be easily incorporated into tunnel, channel or conveyor driers. The incorporation of the SolarWall system also reduces the humidity in the incoming air (because it is heated before entering the building or the drying chamber), which means that the air has been conditioned to absorb more moisture.

Residential or service sector: Climate control of homes or commercial buildings. The air is introduced to the air handling unit (AHU) after being pre-heated by SolarWall, so that the use of conventional heating system is not needed or can be supplementary. The theme of ventilation and heating of spaces is especially relevant in cold weathers, where ventilation and space heating account up to 50% of the energy consumption of the building. In addition, SolarWall systems can heat fresh air, improving the quality of indoor air with benefits for the occupants. The possibility to include SolarWall, for assistance of ventilation is illustrated in Table 2 and Figure 10.

Table 2. Summary of SolarWall assisted ventilation strategies

Result	Impact	Suggested Control Logic
V1 – SolarWall preheats entering air handling unit	Saves heating energy of heating coil of AHU. I2 – Replicability I3 – Cost-effective solutions I4 – Maximization of RES generation I6 – EU construction and GHG reduction	Motorized dampers in ducting control the source of supply to the AHU. 1. The SolarWall intake damper shall normally be closed, and the bypass intake louver damper shall normally be open. 2. Upon a fall in outdoor air temperature below the supply air temperature setpoint, the SolarWall damper shall open proportional to the closing of the intake louver damper to supply preheated air to the air handling unit at the warmest possible temperature below the supply air setpoint.
V2 - SolarWall preheats entering through unit trickle vent	Saves heating energy of unit's radiators. I2 – Replicability I3 – Cost-effective solutions I4 – Maximization of RES generation I6 – EU construction and GHG reduction	Manually operated damper in window block controls the source of supply to trickle vent. 1. Unit resident adjusts a lever to select if the trickle vent should pull air from the SolarWall collector or direct from outside.
V3 - No ventilation plan for SolarWall to integrate with.	No replicability.	

V4 - SolarWall preheats entering air through window block supply	Saves heating energy of unit's radiators but likely is as cost effective due to heat recovery. I2 – Replicability I4 – Maximization of RES generation I6 – EU construction and GHG reduction	Manually operated damper in window block controls the source of supply to window block. 1. Unit resident adjusts a lever to select if the window block should pull air from the SolarWall collector or direct from outside.

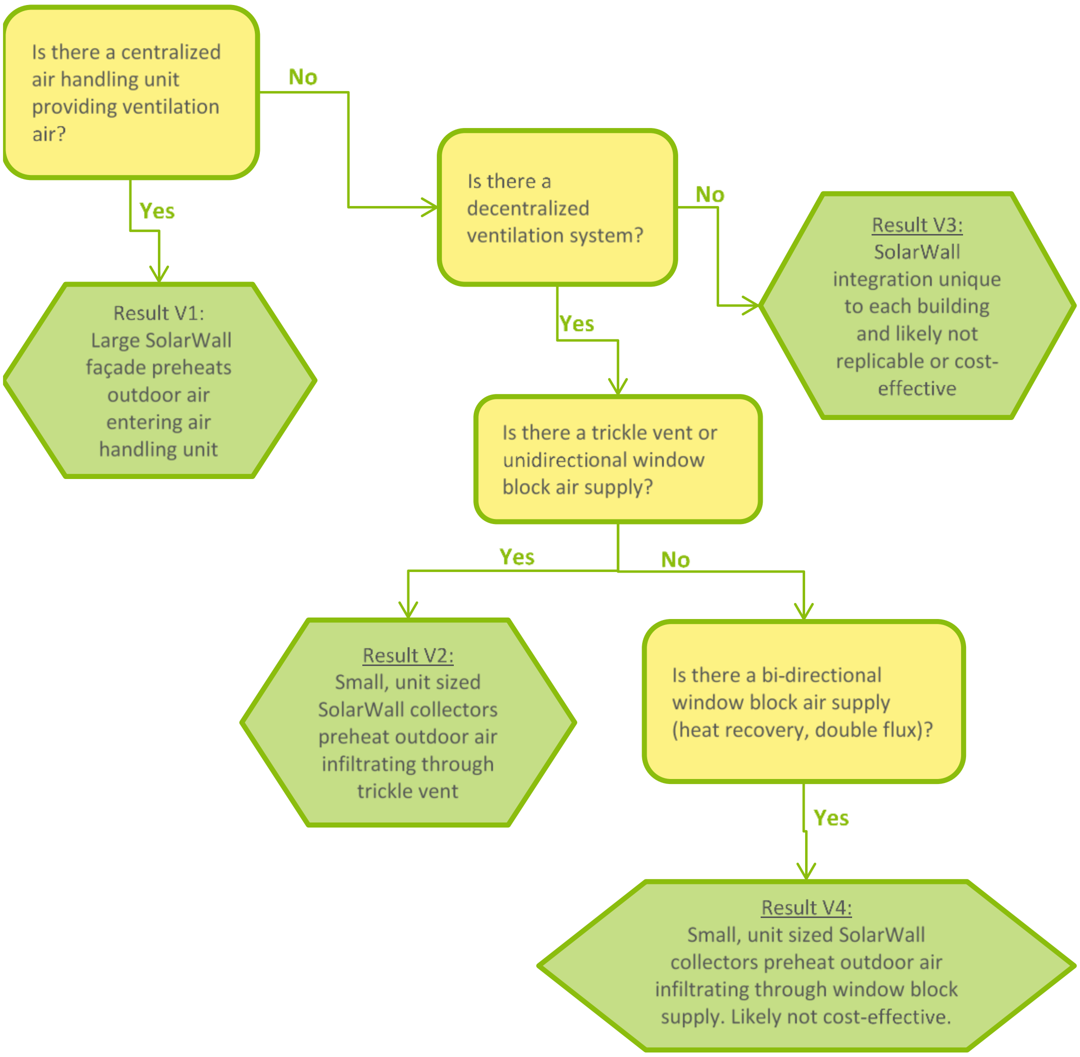


Figure 10. Flow chart of SolarWall assisted ventilation strategy for a building

Livestock industry: SolarWall technology is easily integrated into conventional livestock ventilation systems and preheats incoming air up to 27 °C in these applications. In poultry ventilation, the SolarWall system can be designed to handle the minimum ventilation requirements for the winter, spring and autumn months, as well as the first two weeks of summer for the breeding period. For poultry, typical indoor temperatures start at around 32 °C during the breeding period and are gradually reduced to around 22 °C as the chickens grow. This means that chicken barns (as well as other forms of livestock) may require heat for up to 10 months of the year. In these applications, SolarWall systems have been accredited with the reduction of traditional fuel use by up to 30%. This substantial and continuous reduction in operating costs improves profitability and illustrates why this solar ventilation technology has been widely used in the chicken and pig communities.

1.3 EnergyHub for electricity sharing

1.3.1 Description of the technology

The EnergyHub, developed by Ferroamp, is part of ER7 – 'Building and district energy harvesting management system'. It offers a new approach to maximizing the investment in solar power (see Figure 11) by introducing smart flexibility and technologies that increases the output of the system. It utilizes the possibilities of advanced power electronics for distributed process control, where every component in the system interacts based on common grid regulation algorithms. The unique inverter/rectifier design comes from a patented current equalization function that requires bidirectional energy flows and high-resolution measurements. The measurement capability, the scalable and agile power electronics allow to customize the system with optimal combination of PV panels and storage. Connected and interacting in the EnergyHub DC-nanogrid, all system components work as one system making it easy to monitor, adjust and control the system performance. In addition, the EnergyHub system includes ACE functionality and a smart integrated energy storage that continues utilizing the power modules after sunset.

The brain in the system is the EnergyHub process control that communicates with all system components. EnergyHub gathers relevant information to optimize the energy flow between solar panels, energy storage, the grid, using advanced algorithms. The heart of the system is the Power Module, a 3 x 5 A (3,5 kW) three phase, scalable bi-directional power inverter. The Power Module converts the DC energy from the solar panels and energy storage into AC energy that can be used in the building or sold to the electric grid company. The EnergyHub inverter has a unique function that converts AC from the electric grid into DC to charge the batteries in the energy storage.

One of many advantages with the EnergyHub system is its scalability. This means that it can be built for any power demand by adding power modules until the desired capacity is reached, from a single building to blocks of buildings. EnergyHub is available in a wall mounted enclosure that can be equipped with up to 4 Power Modules (3,5 kW - 14 kW) or in the EnergyHub XL system where modules are housed in 19" rack enclosures with up to 8 modules each.

Ferroamp also developed application programing interfaces (API) available for customers that have custom needs for monitoring and controlling the energy flow. These interfaces can be used for integration with building automation systems, EV charging stations or external control systems.

All EnergyHub system components are controlled in one single power process which makes the EnergyHub system truly unique and opens the door for more efficient energy management.

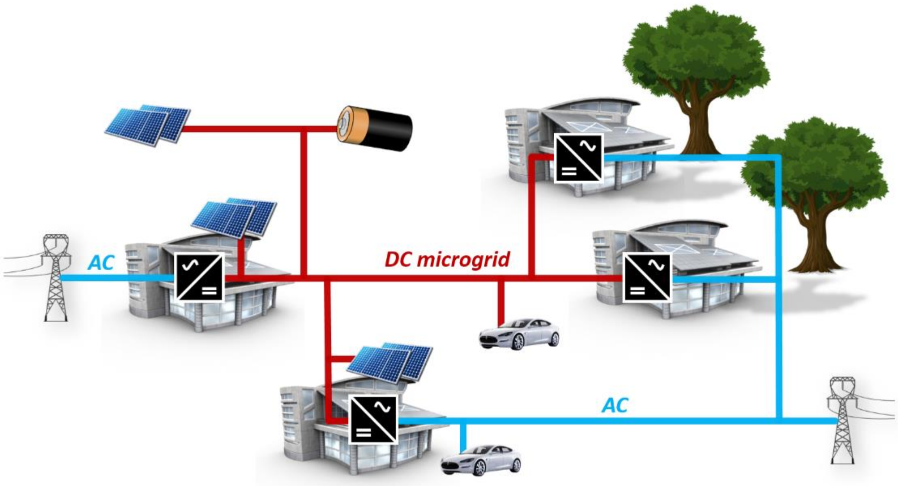


Figure 11. EnergyHub system on district DC grid

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°768766

1.3.2 Main results

In this project, Ferroamp optimizes the energy flow of the EnergyHub system by examining the operational parameters for each node individually. The optimization of a node or system can be based on different use cases, such as:

- Sharing PV installation
- Maximizing self-consumption
- Peak-shifting to reduce power tariffs
- Exceed power limit impeded by AC grid infrastructure

Ferroamp has also developed a district DC grid visualization for district DC grid power and energy management that is built on-top of Ferroamp's cloud portal. The visualization tool makes it possible to see the energy flow between the DC grid and the different buildings. Ferroamp has performed in testing in-house as well as system concept testing. One of the testing results is illustrated in Figure 12.

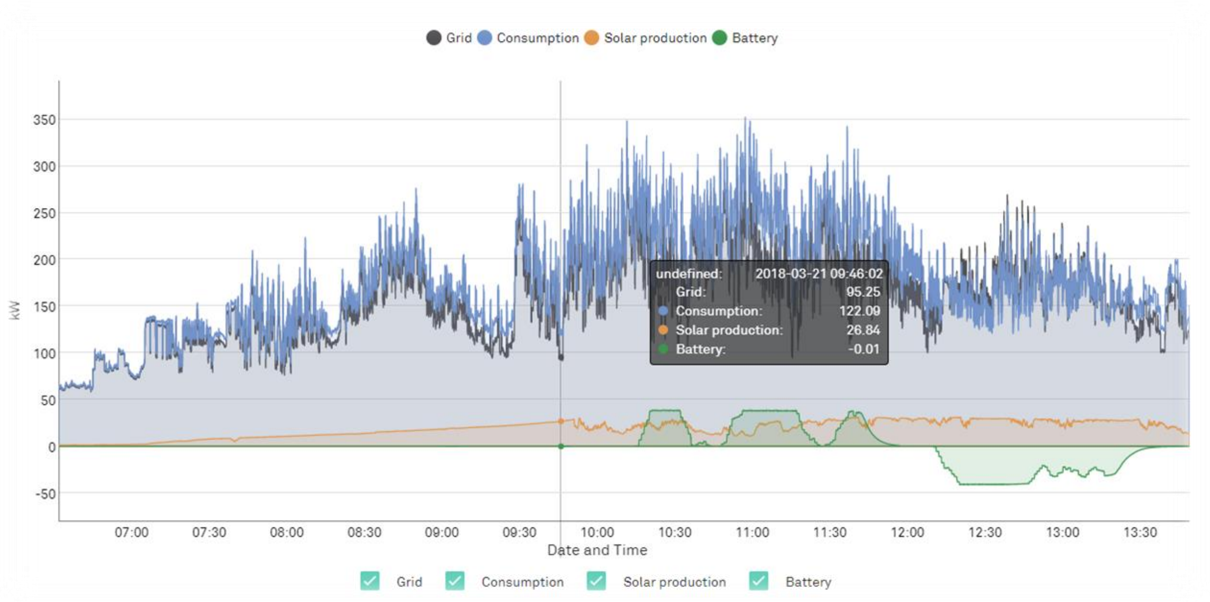


Figure 12. System concept testing results of EnergyHub system

1.3.3 Design drivers and typical applications

The EnergyHub system design topology allows to build systems suitable for any application, ranging from single-family houses to larger multi-family installations or commercial MW solar plants. This design offers higher redundancy as production can be maintained in case of a single module failure. The modules can easily be replaced in the field with minimal influence on system output.

Besides being a fully integrated solar power system with integrated energy storage, the EnergyHub offers functionality where limited or no solar power is available. EnergyHub can provide ACE current equalization for facilities or power companies, it can be used for reactive power compensation for industrial customers or in the grid and can also provide power peak shifting or shaving, or powerful EV charging with energy storage.

By keeping as much of production and consumption on DC grid, unnecessary conversion losses can be avoided and thus resulting in higher efficiency.

1.4 Façade-integrated decentralized ventilation

1.4.1 Description of the technology

Façade-integrated decentralized ventilation is part pf ER4 – 'Solar window package' solution. Mechanical decentralized ventilation is the possibility to realize the air renewal by using a number of decentralized ventilation units (or DVUs) exchanging air across the building envelope rather than by using a single centralized air handling unit connected to the ventilated spaces with air ducts. This kind of solutions has recently gained the attention of the HVAC market and a variety of solutions have been developed for the tertiary and residential sectors. In simpler solutions, DVUs operate with a single airflow that is intermittently directed from the dwelling to the exterior and vice versa. In this case, the pressure drop is minimal and the heat recovery, if any, is realized through a thermal mass located in the duct connecting indoor and outdoor. In other solutions, DVUs run separate airflows for supply and return air and the heat recovery is realized through a cross-flow or counter-flow heat recovery unit installed in the casing. In both cases, the air is usually filtered before the admission in the ventilated spaces.

Larger DVUs can integrate additional functions to ventilation, such as the delivery of space heating or cooling or humidity control. In the residential context, small sized units suitable for the integration in window mono-blocks are however quite limited in the range of offered services (typically only ventilation and heat recovery) because of the limited space for the installation. The maximum airflow rates that are provided by DVUs are also linked to their size. Typical airflow rates for DVUs developed for residential applications are in the range of 50-150 m^3/h. As exemplification, *Thesan Airacare ES* is a double flow DVU that can run up to 42 m^3/h fresh air and can recover heat from the exhaust air. The noise reduction is 53-55 dB depending on whether the shutters are opened or closed and the sound power (LwA) varies between 37 to 51 dB depending on the speed of the fans. Figure 13 shows its internal components (fans, heat recovery unit, filters) and structure.

Due to the low airflow rates and the lack of an air distribution network in the dwellings, a number of DVUs is usually installed in each flat based on the number of closed spaces where mechanical ventilation is desired. Alternative solutions for the extraction of exhaust air from kitchens and toilettes might be required if such spaces are not perimetral.

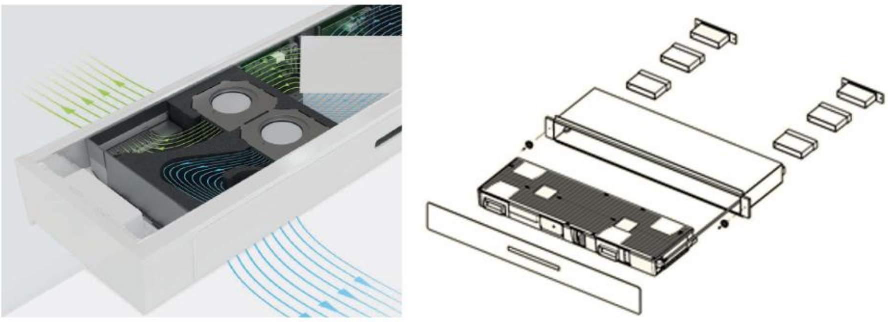


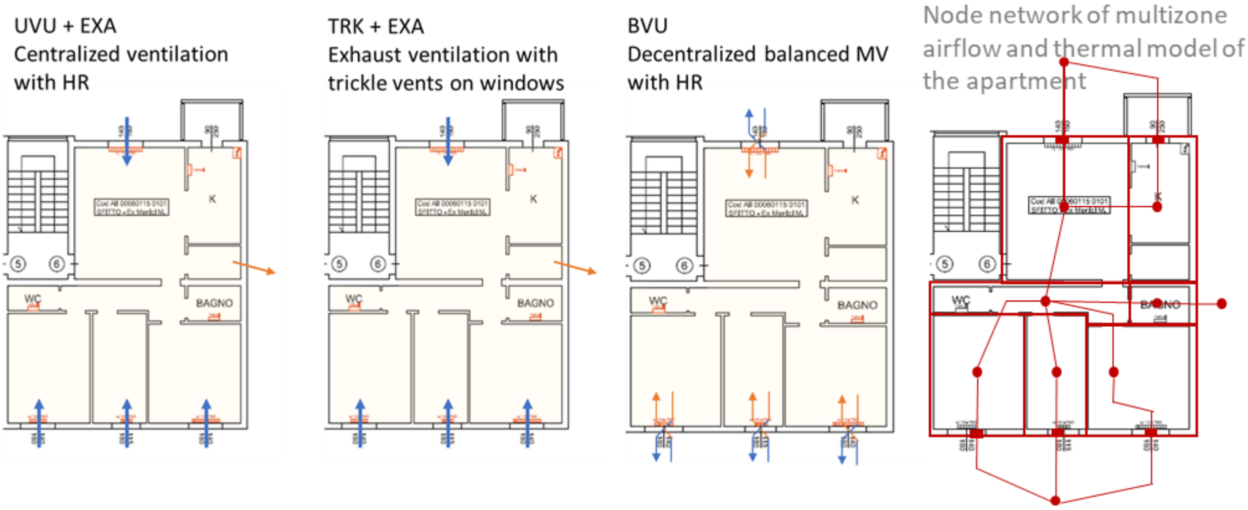
Figure 13. DVU model Thesan Aircare ES, https://www.thesan.com/it/prodotti-vmc/aircare-es/

The façade-integration of DVUs consists in the installation of the ventilation units in window-monoblocks. The size of the integrated DVU is of high relevance as it is hosted in a cavity localized on the side of the window frame. The access to the ventilation unit from inside or outside must be improved to enable an easy mantainance. Moreover, the themes of the detailled design of the contact surface between the casing of the ventilation unit and the surrounding elements of the window mono-block are tackled to mitigate or solve the issues related to water permeability, thermal bridges and noise transmission.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°768766

1.4.2 Main results

The performance of different ventilation concepts are compared in terms of airflow, IAQ, thermal comfort and energy demand (example results shown in Italy and French demo climates). The performances are analysed through coupled thermal/airflow simulations (Trnsys+Trnflow) on a reference apartment model with 3 different levels of air-tightness (n50 = 0.6 h-1, 1.5 h-1, 3.0 h-1) and window operation (for summer ventilation), as shown in Figure 14. The results of the analysis are summarized in a SWOT matrix (Table 3).


UVU + EXA
Centralized ventilation with HR

TRK + EXA
Exhaust ventilation with trickle vents on windows

BVU
Decentralized balanced MV with HR

Node network of multizone airflow and thermal model of the apartment

Figure 14. Different ventialtion modes for a reference apartment in summer

Table 3. SWOT analyssis of different ventialtion modes

Modes	Strengths	Weaknesses	Opportunities	Threats
Decentralized ventilation unit (BVU)	Low heating demand if high building air tightness Normal level of IAQ	High risk of overheating – need ventilated cooling solutions to ensure thermal comfort over summer season	Can be energy autonomous if PV + battery are integrated in the window block High replicability of the solution since no ductwork is needed and can be easily installed Supply air can be preheated by solar wall	Heat pump cannot use exhaust air as source. Ventilation unit can be noisy and therefore shut off by users.
Centralized ventilation system (UVU+EXA)	Very good IAQ because of better air distribution	Higher heating demand and energy consumption for ventilation due to heat and pressure losses	Lower overheating risk because of higher air changes Supply air can be preheated by solar wall	Exhaust air heat is recovered within the AHU and cannot be used by the heat pump. Installation works might be invasive.

Exhaust ventilation with trickle vents (TRK+EXA)	Acceptable IAQ level (category 2 for over 80% of the occupied time) Low heating demand if high building air tightness	No control on air supply temperature	Centralized exhaust airflow can be used as air source by the heat pump High replicability of the system since centralized exhaust ventilation systems are quite common in existing multistory residential buildings Natural ventilation by opening windows increases its performance during summer season Supply air can be preheated by solar wall Lower installation and operation costs	Potential local thermal discomfort due to draft risk during cold season Need to eliminate or minimize all potential air leaks in the building envelope to prevent unwanted moisture or pollutants transport from adjacent dwellings.

1.4.3 Design drivers and typical applications

The application of decentralized mechanical ventilation in the residential context is attractive for a number of reasons. First of all, the issue of ventilation is relevant in all buildings where the envelope guarantees a high level of air tightness (new constructions and retrofitted buildings). As good quality windows and doors limit uncontrolled air infiltrations, higher ventilation rates might be needed to guarantee an adequate number of hygienic air changes and prevent all problems connected to insufficient ventilation, from high concentration of air pollutants (CO_2, VOCs etc.) to the growth of mold. Another issue that has become critical in the last decade is the pollution of ambient air, especially in large cities and in the proximity of pollution sources as industries or highways. The filtration of ambient air is then becoming indispensable in urban contexts to avoid the admission of the contaminats and maintain an healthy environment in the occupied spaces.

Mechanical ventilation can effectively answer these needs as it enables to control the air exchange between indoor and outdoor in terms of air quality and airflow rates. In this context, the installation of DVUs represents a very interesting option, as it allows to perform mechanical ventilation also in dwellings where there is no pre-existing air distribution network, making this solution ideal for the restructuring and non-invasive retrofit. From the energy perspective, the ventilation heat losses are greatly reduced by the heat recovery unit in the ventilation unit, which transfers heat from the exhaust to the fresh airflows. As consequence, the thermal load of the dwellings decreases and the annual energy bills are reduced. With respect to centralized solutions, the pressure head of the ventilation unit is usually lower due to the lack of external ducts and, even though the efficiency of the fans is lower in smaller applications, it is possible to achieve electricity savings. Moreover, the adoption of demand-controlled ventilation strategies, that is “the space is ventilated only when needed” can further reduce the ventilation heat losses and the electrical consumption of the fans.

Concerning the façade-integration of DVUs, the main advantage is that the whole solution is designed, sold and installed as a unique package. In this way, it is possible to realize a solution of higher quality, being the design of the components adapted and optimized for a full integration. The critical nodes of the coupling between ventilation unit and window monoblock are studied in detail and solved with the development of appropriate technological solutions. Ideally, the integrated solution can be pre-fabricated in factory by specialized technicians rather than on site, reducing the time and increasing the quality of the installation. Finally, the costumer deals with a single company that is hold responsible for the whole solution.

1.5 Trickle vents

1.5.1 Description of the technology

Trickle vents (shown in Figure 15) are part pf ER4 – 'Solar window package' solution. They are natural ventilation devices that serve as inlet vents for direct outside air. Trickle vents provide background ventilation using natural driving mechanisms (wind and stack-induced pressure), but can also be used in conjunction with mechanical exhaust ventilation systems. Trickle vents are typically incorporated into the window frame and manually operable from the inside through an interior flap, that allows opening and closing them with one or more (up to 6) intermediate positions.

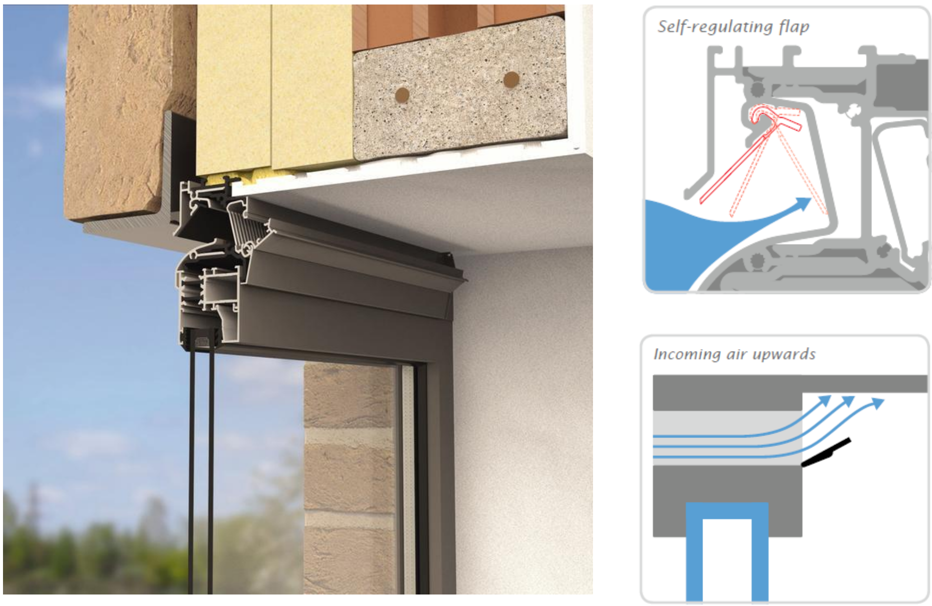


Figure 15. Window with trickle ventilation (left) and detail of self-regulating exterior flap (right above) and interior flap (right below). Source: Renson

Trickle vents are **pressure-controlled** or **self-regulating**: an exterior flap moves to regulate incoming air flow according to pressure difference between indoor and outdoor due to stack and wind effects (Figure 15). The inlet area becomes smaller at high pressure differentials (ΔP > 12 Pa) and it becomes larger at low pressure differentials (ΔP < 12 Pa). This allows for better ventilation losses control during the heating season.

Trickle vents can be classified according to mounting type into:

- **Surface-Mounted** trickle vents, where flap ventilators are integrated in the window frame.
- **Glazed-In** trickle vents, where flap ventilators are glazed in the transom/mullion.

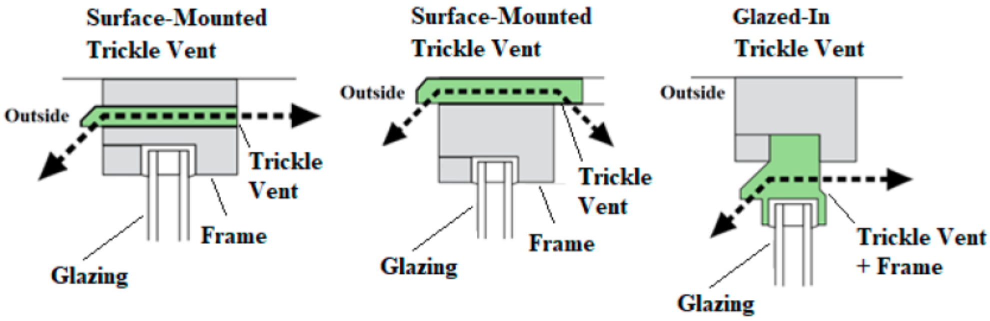
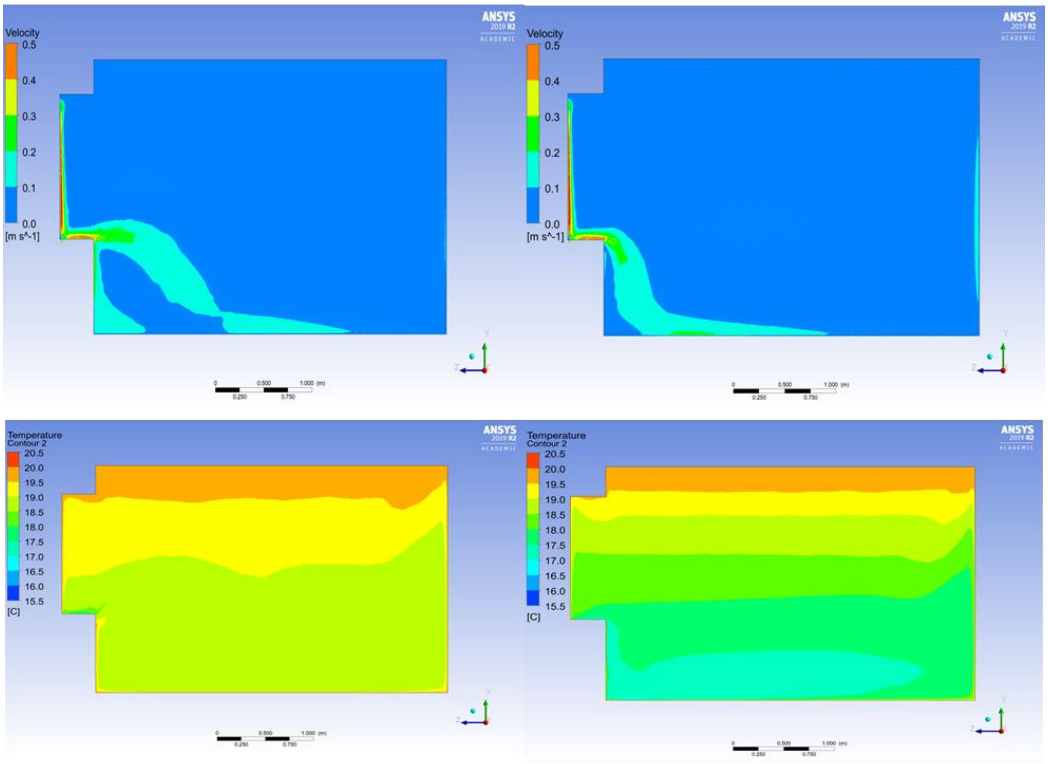


Figure 16. Surface-Mounted (left) and Glazed-In trickle vents (right). Source: [1]

Trickle vents available on the market have the following optional: insect screen, thermal break, external hood for weather protection, sound absorber, motorised flap control and supporting mechanical ventilator.

1.5.2 Main results

A CFD analysis is conducted to evaluate the draft risk of the trickle vents integrated the window block system in reference conditions: T_{out} = -6°C; T_{in} = 20°C; inlet air velocity 0.2 m/s; with (daytime) and without working (nighttime) radiator. The resulting air velocity and temperature distributions demonstrate that: (1) both cases can be considered comfortable according to EN 7730 standard, and (2) relatively high air velocity and colder air temperatures can be experienced within 0.5 m in case there is no radiator. But this effect becomes less sensible if we move 1m from the center of the window. Figure 17 shows the simulation results.



Radiator on

Radiator off

Figure 17. CFD analysis of the trickle vents integrated the window block system

1.5.3 Design drivers and typical applications

Main design drivers for trickle ventilation are the ventilation capacity (equivalent area, airflow at certain pressure difference), acoustic attenuation (sound reduction), air tightness (air permeability), filter efficiency, security and controllability.

Trickle vents are not convenient in cold climates due to the high draft risk they can cause. Typical designs include some precautions to mitigate draft risk. In fact, most trickle vents applications are on top of the window frame or glazing (at ca 1.7 m above floor) and interior flaps are designed in a way to deflect cold air upwards. They are also recommended to be installed above radiators so that the upward draft of warm air mixes with the cold inlet air and reduces risk for cold drafts.

Trickle vents generally have a sound insulation level of around 30 dB in open position, which is considerably better compared to the one of an opened window and also lower than the sound power generated by a façade-integrated decentralized ventilation unit (see section 1.4). Sound reduction can be obtained by inserting an acoustic foam within the window frame. This allows to increase the Sound Insulation level up to 48 dB leading to a reduction in ventilation capacity since the acoustic foam causes a higher pressure drop. Acoustic performance shall be considered for the application of trickle vents depending on room type and outdoor noise levels.

Trickle vents are usually endowed with an insect/dust screen and have optional fine dust filter application, in case outdoor environment is high polluted or occupants suffer of hay fever. This obviously reduces ventilation capacity causing a higher pressure drop. Thermal bridging and condensation risk need to be verified through appropriate calculation methods and tools for the specific window design. Due to the low opening area, trickle vents are burglar proof. Background ventilation can be guaranteed even during not occupied periods reducing overheating risk in summer.

Trickle vents opening can be controlled through the building management system according to outdoor temperature, indoor CO_2 concentration and relative humidity by adjusting the levels of opening vents. In case of manually controlled vents, during heating season there is a higher risk of occupants closing the interior flap because of draught occurrence. During summer season, having the position of the controlled air inlet at the very same position of the window can be an advantage, since occupants can instantly decide to operate both in a more synergic way as well as guaranteeing background ventilation even during non-occupied period.

The general advantage of trickle vents is their integration into the block system at lower extra-cost for manufacturing and for maintenance/operation. Integrating such devices in the window block bring advantages in terms of natural ventilation, as occupants will have the possibility to guarantee air exchange both through window opening and trickle vents at no extra operation energy cost.

2. Heating and ventilation system concepts

2.1 Solar assisted ambient air heat pump system

2.1.1 System description

Solar assisted ambient air heat pump system is part pf ER6 – 'Renewable harvesting package to heat and ventilate' solution. According to the IEA SHC Task 53 [3], the definitions of solar assisted air source heat pump system boundaries (Figure 18) mainly contain five types. The origin air source heat pump system is shown in orange dashed line (HP), which contains heat pump only. Adding solar collector system, which is concluded in green dashed line, the system is called solar assisted air source heat pump system (SHP), while above two system types are both without circulation water pump. System boundary SHP þ does include these pumps (blue dashed line). Solar assisted air source heat pump system with PV arrays (SHPPV) is shown in red dashed line. It includes the PV array but without battery storage. With battery storage system, the system boundary is called solar assisted air source heat pump system.

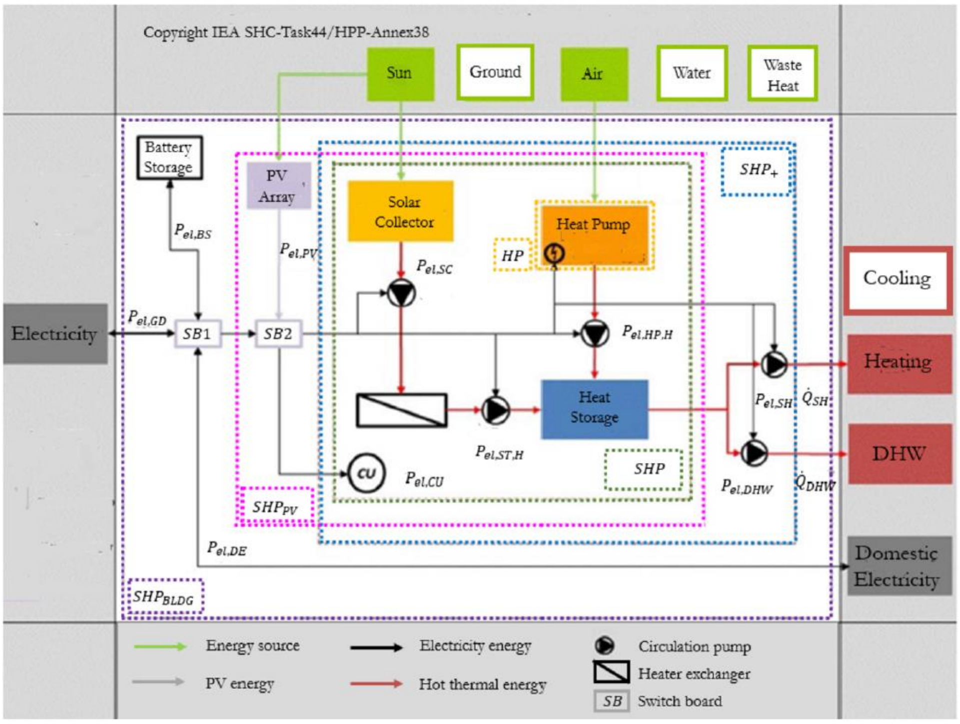


Figure 18. Different system boundaries (figure based on the ongoing Task 53 [3] work)

The coupling of transpired collectors and an air-to-water heat pump was studied in Energy Matching and resulted in the elaboration of the energy concept shown in Figure 19 and described below. The main energy generation source of the system is an air-to-water heat pump that uses ambient air as heat source/sink. The ambient air can be pre-heated by transpired solar thermal collectors before the inlet to the heat pump, so that the heat pump can work in more favourable conditions and reduce its electrical consumption when working in heating mode. The passage of ambient air in the transpired solar collectors and in the connection ducts causes an additional pressure drop that must be compensated by the fan in the heat pump.

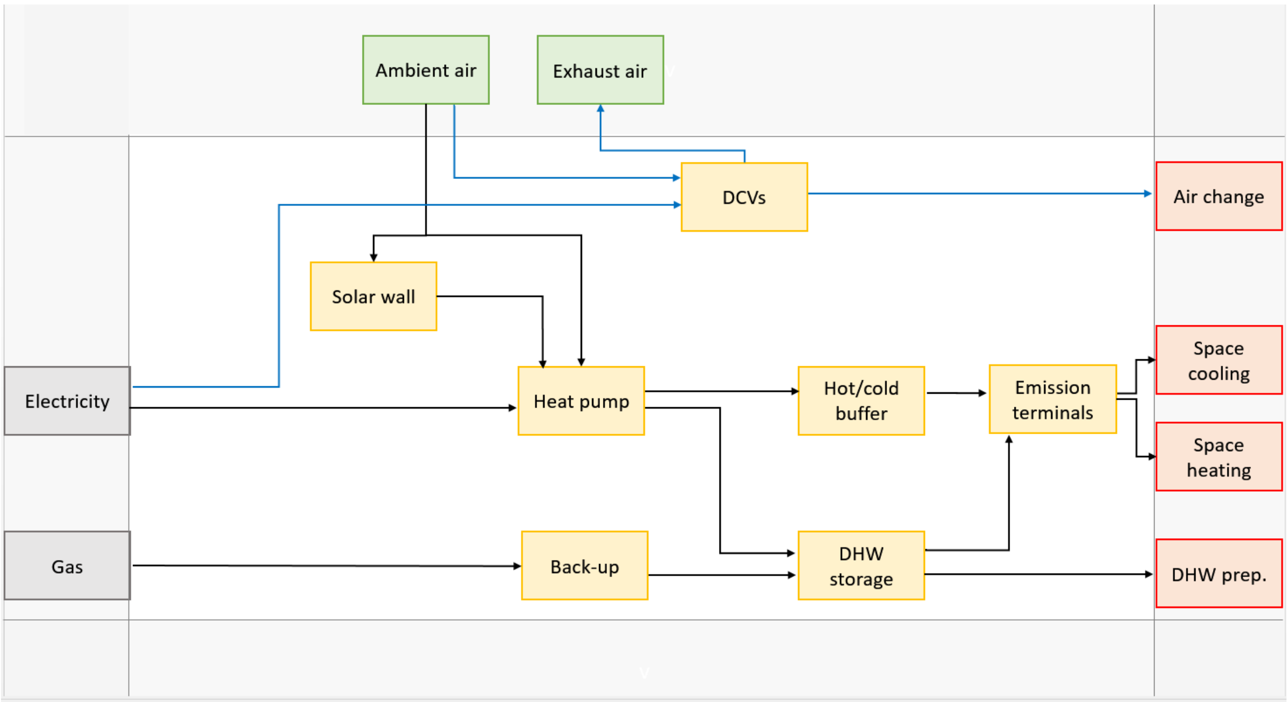


Figure 19. Layout of the solar assisted air-source heat pump energy concept.

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Traditional air-to-water heat pumps, however, are not usually coupled with transpired collectors and ducts at the source side and thus (1) the fan is not sized to provide this additional pressure head and (2) their casing of the heat pump is not designed to be easily ducted. These two issues can be solved by using an exhaust air heat pump in place of a classic air-to-water heat pump, as shown in Figure 20. In this case, the evaporator is connected to an external ventilation unit equipped with an air-to-fluid heat exchanger. For this application, the ventilation unit is not used to extract exhaust air from the dwellings as in typical installations, rather to run ambient air through the transpired collector. A better fit to the technological requirements of the Energy Matching system is then found, as the ventilation unit of an exhaust air heat pump is built to be ducted and can offer an external pressure drop exploitable to run the ambient air through ducts and transpired solar thermal collector.

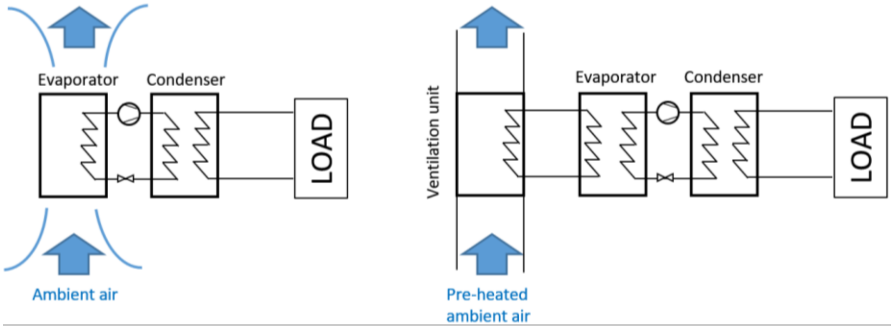

Figure 20. Schematic structure of an air-to-water heat pump (on the left) and an exhaust air heat pump (on the right)

Two water storages are used to decouple energy demand and generation and a centralized gas boiler (or alternatively an electric resistance) is used as back-up energy generator. The distribution system is water-based and reaches the emission terminals (fan coils, radiators etc.) in the dwellings through the pre-existing pipework or with the use of additional pipes installed either in the stairways or in the facade.

Concerning the issue of ventilation, decentralized ventilation units (DVUs) are installed in the window mono-blocks of the spaces where ventilation is desired. DVUs work independently from the energy generation and distribution systems and the only possible interference occurs if the thermal power is distributed via air-based emission terminals (e.g. fan coils). In this case, the positioning of the openings and the possibility of implementing push and pull ventilation strategies must be carefully evaluated.

The ventilation unit of exhaust air heat pumps is typically installed on the rooftop, where the exhaust air and fumes are collected. Also in the Energy Matching application, it is convenient to install the ventilation unit on the rooftop, where the air from the transpired solar collectors is collected. The heat pump, the water storages and the back-up energy generation system can be installed where convenient, depending on space availability and floor load capacity. The distribution of hot and cold water is centralized and thus the laying of a new pipework is required in case it is not present beforehand.

As regards the transpired solar collectors, they are vertically installed on the building façade and their productivity can be limited by unfavourable azimuthal exposure or external shading due to nearby buildings or trees. The air running through the panels is collected by a plenum connected to the ventilation unit of the heat pump via ducts installed on the rooftop.

The DVUs are installed in the window mono-blocks and, due to their size, it has to be checked whether the resulting window area is compliant with the minimum required by law for refurbished residential buildings. The installation of air ducts is unnecessary as the air exchange with the internal spaces is directly realized across the building envelope.

2.1.2 Main results

The air source heat pump systems assisted by solar energy have drawn great attentions, owing to their great feasibility in buildings for space heating/cooling and hot water purposes. However, there are a variety of configurations, parameters and performance criteria of solar assisted ASHP systems, leading to a major inconsistency that increase the degree of complexity to compare and implement different systems. By a comparative literature review, the performance of various ASHP systems are evaluated from three main solar sources, such as solar thermal (ST), photovoltaic (PV) and hybrid photovoltaic/thermal (PVT). In comparison to the other technologies as it is earlier stated that PV-ASHP has best techno-economic, which performs best in average with coefficient of performance (COP) of around 3.75, but with moderate cost and payback time [4], which is thus mainly investigated in Energy Matching project.

2.1.3 Opportunities and barriers

The main opportunities and barriers to the implementation of this energy concept are listed below.

Table 4. SWOT analysis of solar assisted heat pump concept

Strengths	Weaknesses	Opportunities	Threats
*The installation of air ducts is not needed *Filtration of external air before admission in occupied space *Reduction of the ventilation losses thanks to a high-efficiency heat recovery unit installed in DVUs *Reduction of the electricity consumption of the heat pump thanks to the pre-heating of the ambient air before the admission in the evaporator *Robust solution due to separation between energy system and mechanical ventilation system	*Additional maintenance needed by DVUs *Additional space needed for the installation of the DVUs in the window block	* The electrical consumption of the heat pump can be covered with the use of PV panels *Integration of additional functions in the window mono-block, as PV panels + battery to cover electricity consumption of DVUs and/or automated shading *Generation and delivery of cooling power, if the system is designed also for this scope	*DVUs can be noisy and therefore shut off by users with negative drawbacks on the air quality *Proximity to pollution or noise sources can be affect indoor environmental quality due to delocalization of DVUs in the building envelope *Unfavourable façade exposure and external shading as well as unfavourable weather conditions (low solar irradiation, strong winds) can severely limit the benefit from transpired solar thermal collectors *If the performance of the heat pumps is already good (favourable climate, working conditions etc.), the potential energy saving from transpired solar thermal collectors is limited

2.2 Centralized exhaust air heat pump system for multiple buildings

2.2.1 System description

Centralized exhaust air heat pump system is part pf ER6 – 'Renewable harvesting package to heat and ventilate' solution. The system concept is shown in Figure 21 and is the system used at the Swedish demonstration site. A very similar design is also used in the French demonstration site, but in that case there are two buildings. There is a centralized heating plant comprising a heat pump and back-up boiler. These heating units supply heat directly to the heat emission units via a small buffer storage, matching the space heating load by modulating their output power. Only the heat pump supplies heat (at full power) to the DHW storage. The heat supply to the heat pump comes from recovery of heat from the ventilation air via an air/brine heat exchanger and circulation loop to the heat pump. An anti-freeze mixture is used in this loop as the heat pump can operate with supply temperatures below zero. In Swedish systems, heat from all exhaust air is normally recovered, meaning that there needs to be good filters in the heat recovery units and that they need periodic replacement due to dirt build-up, principally from the kitchen. There are sometimes filters at the kitchen extraction points as well. This system design is very well suited to buildings that already mechanical ventilation without heat recovery, as there is no additional cost for new ducting.

This concept can be used in a single building or can be applied to multiple buildings, as is the case in the Swedish demonstration with three buildings. Each building needs to have one or more heat recovery units in the attic, and the circulation loops from these are all connected to a single heat pump unit in one of the buildings. Similarly, the heat distribution for both space heat and DHW is distributed to all buildings via underground culverts from the centralized thermal plant. Hot water circulation is used to ensure that there is only a small delay for delivery of sufficiently hot DHW in the flats. There are six pipes in the culverts:

- Supply and return to/from the emission terminals (space heating).
- Hot water (DHW) supply to the flats, and hot water return circulation pipe.
- Two pipes for brine circulation loop for heat supply to the heat pump (from heat recovery units).

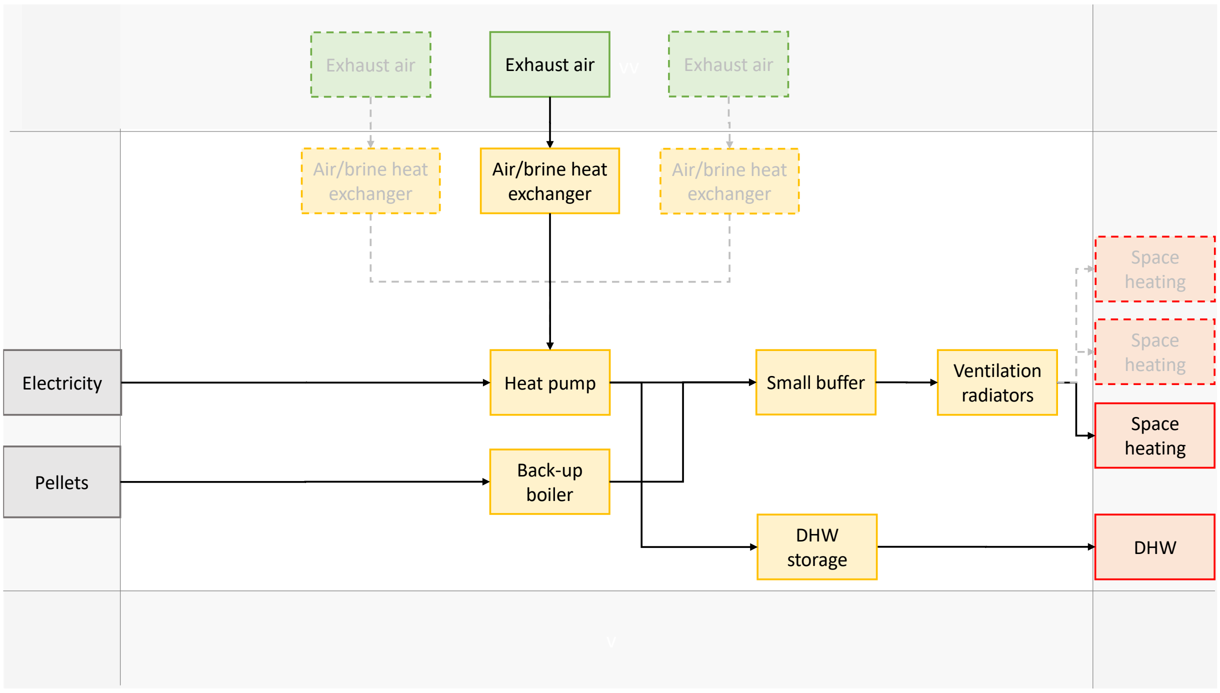

Figure 21. Example layout of centralized exhaust air heat pump energy concept

The operation of the exhaust air ventilation creates an under-pressure zone in the whole building and induces fresh air to enter the apartments through trickle vents located in the envelope. In the Swedish demonstration

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site, the air inlets are located behind the radiators and the inlet air is constrained to flow through the so-called ventilation radiator, see Figure 22. Ventilation radiators have significantly better heat exchange with air than normal radiators and can thus be operated at lower temperatures than traditional radiators for a given radiator size. This lower operating temperature leads to an improved COP of the heat pump compared to use with traditional radiators. The improved heat transfer in the radiators is due to two factors: lower inlet air temperature as ambient and not room air is heated; improved convection on the heat exchange surfaces as the air is sucked through the radiator due to the exhaust air fan. In the French demonstration case, the trickle vents are instead located in the window monoblock, and traditional column radiators are used as emission terminal.

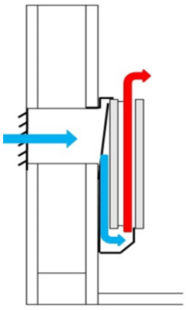

Figure 22. Ventilation radiator, where fresh air is sucked into the building through a vent in the wall behind the radiator and forced to flow through the radiator

2.2.2 Main results

The amount of heat that can be extracted from the exhaust air is dependent on the ventilation rate, which is generally fixed at the national requirements for hygienic air, in Sweden corresponding to 0.35 l/m^2·s, which is roughly 0.5 air changes per hour for normal ceiling heights. This is not enough to cover the heat load in the winter, and thus a back-up boiler is required, in this case a pellet boiler. Due to the modular capabilities of the heat pump from Nibe (see section 1.1), a larger sized heat pump with additional heat source such as ambient air or ground heat exchanger could be used instead of the back-up boiler. For the Swedish demonstration site the heat pump is calculated to deliver 56% of the heat at an SPF of 3.52 while for the French demonstration site the heat pump should deliver 80% of the total heat with an SPF of 2.97. The heat pump fraction is lower in Sweden due to the high space heating demands (see Figure 23), while in France the SPF is lower due to higher design temperatures for the radiators. The heat pump fraction of the total heat supply is very dependent on whether the PV excess is stored as heat or not (see details in section 3.2).

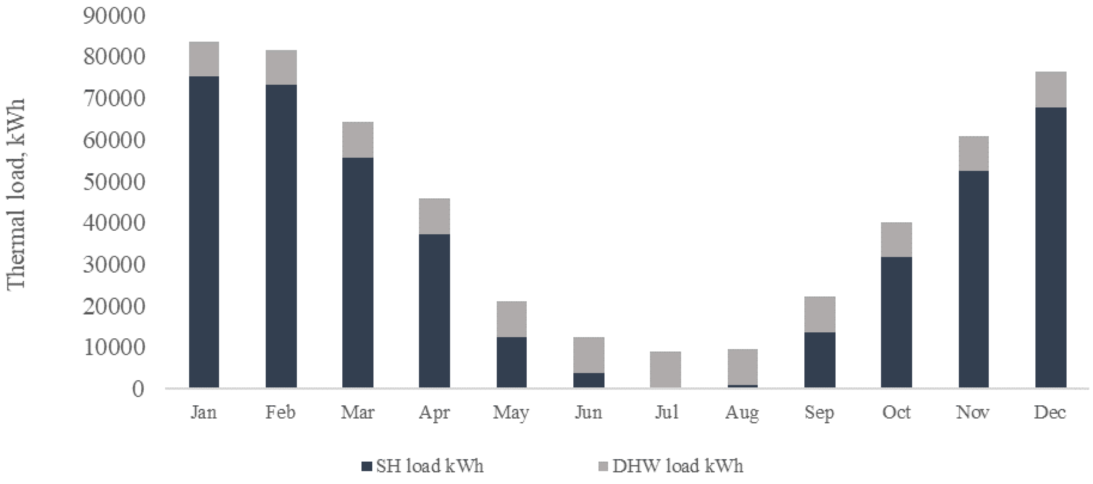

Figure 23. Annual thermal demand of the building cluster in Swedish demo case

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Previous projects in Sweden have shown that, if the infrastructure is already in place, a centralized system based on an exhaust air heat pump is more cost-effective than centralized heat recovery ventilation [5].

2.2.3 Opportunities and barriers

The main opportunities and barriers to the implementation of this energy concept are listed below.

Table 5. SWOT analysis, centralized exhaust air heat pump system for multiple buildings

Strengths	Weaknesses	Opportunities	Threats
* High seasonal performance factor due to high inlet air temperatures *Ventilation radiators pre-heat inlet air giving good thermal comfort and also increase the heat pumps seasonal performance factor *Heat recovery even during the summer for hot water demand	*The exhaust air as source cannot cover the whole heating demand of the building, so two sources are required *Needs regular replacement of filters if exhaust air from kitchen also to be used *Needs centralized heat and hot water distribution system	*Cost-effective renovation solution for buildings that already have centralized mechanical ventilation but no heat recovery *Use of PV power to run the heat pump *Could also provide cooling, if fan coils are used for heat emission. Ventilation radiators provide only limited cooling capacity	*Buildings without centralized heat and hot water distribution require new distribution system

2.3 Solar assisted exhaust air heat pump system

2.3.1 System description

Solar assisted exhaust air heat pump system is part pf ER6 – ‘Renewable harvesting package to heat and ventilate’ solution. In this layout (Figure 24), an exhaust air heat pumps (EAHP) is integrated with transpired air solar collectors (UTSC), such as SolarWall. In the proposed system, hot air from the UTSC is mixed with exhaust air recovered from buildings and is used to increase the inlet brine temperature of heat pump using air to brine heat exchanger. The realised benefits of higher air volume and air temperature will result in increased HP capacity and COP, and thus the reduction in electricity consumption.

This system concept is studied in a case in a building cluster with a centralised heating system for both space heating and DHW demand using distribution networks through culvert. The energy sources consist of a centralised EAHP and an auxiliary pellet boiler. EAHP is coupled with the exhaust ventilation system of the building. The fans of the ventilation system operate continuously in buildings attic, and the air from building rooms is extracted and delivered to the heat pump using air ducts. Fresh makeup air is drawn in the building using trickle vents provided in each room. The EAHP is an integrated unit of air/brine heat exchanger and a brine/water heat pump and is designed based on the ventilation air rate of 0.35 $\mathrm{l/m^2}$ s available from the various building zones. The exhaust air is used to increase the inlet brine temperature to the HP evaporator, and this is achieved using air to brine heat exchanger. The capacity of the heat pump is limited by the volume flow rate of exhaust air recovered from the buildings.

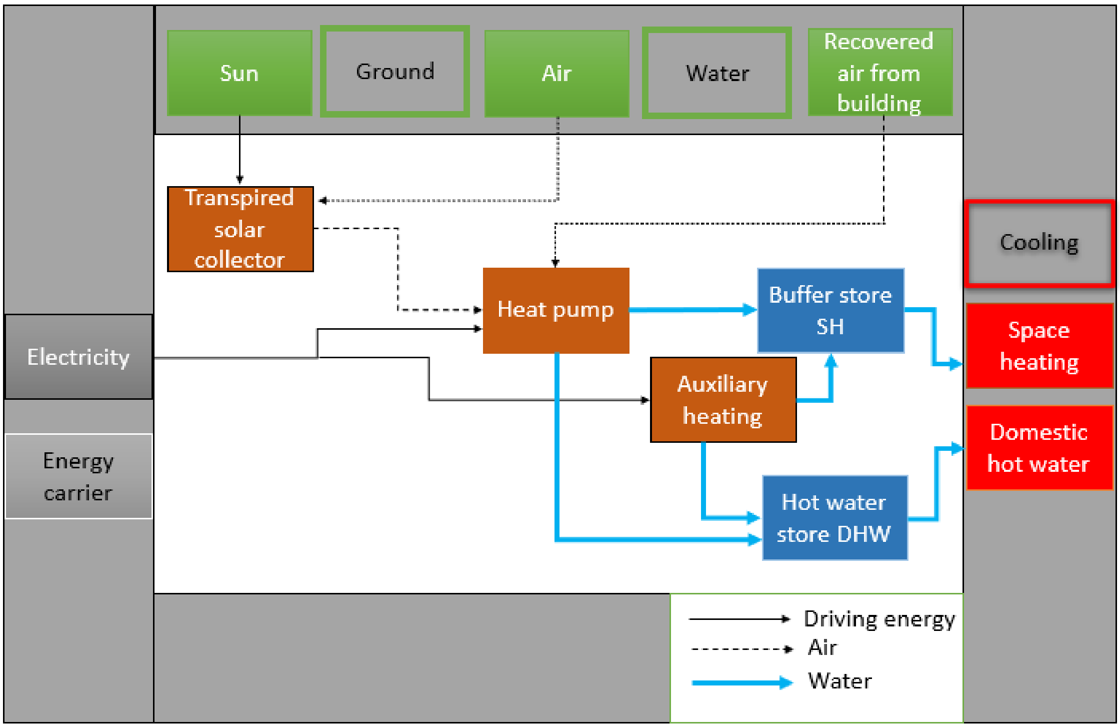

Figure 24. Solar assisted exhaust air heat pump system

2.3.2 Main results

Figure 25and Figure 26 respectively illustrates the effect of flow rate strategy on system performance and various energy flows in the system. The main results are summarized as below:

- The integration of solar collectors with an EAHP has a positive impact on both system and component performances. The seasonal performance factor of the overall system is improved due to higher COP of heat pump, resulting into a lower electricity consumption.
- The optimisation of the air flow rate of in the solar collector is critical and can affect the overall system performance. Rule based algorithms are developed to effectively control the air flow rate in the collectors, considering a system performance perspective.

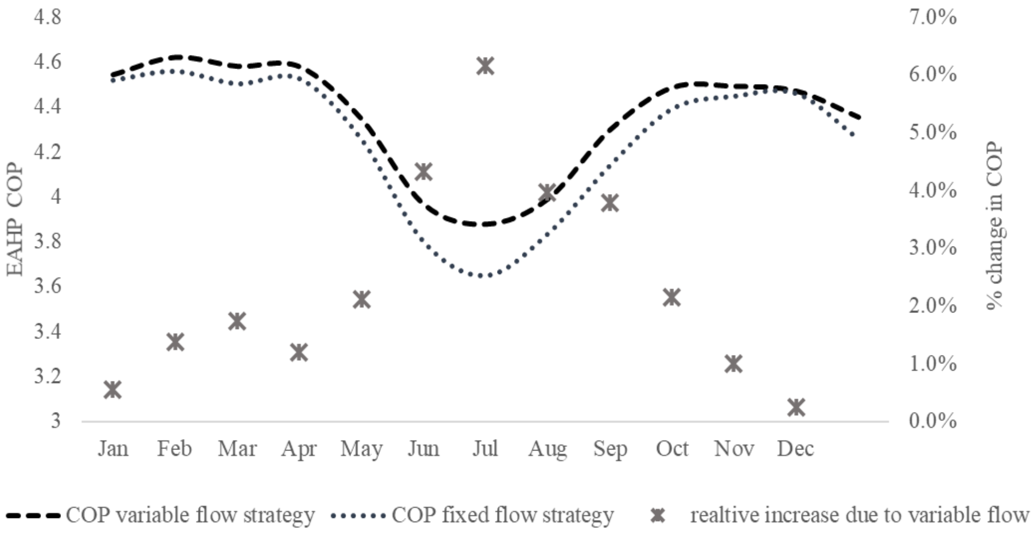

Figure 25. Effect of flow rate strategy on system performance

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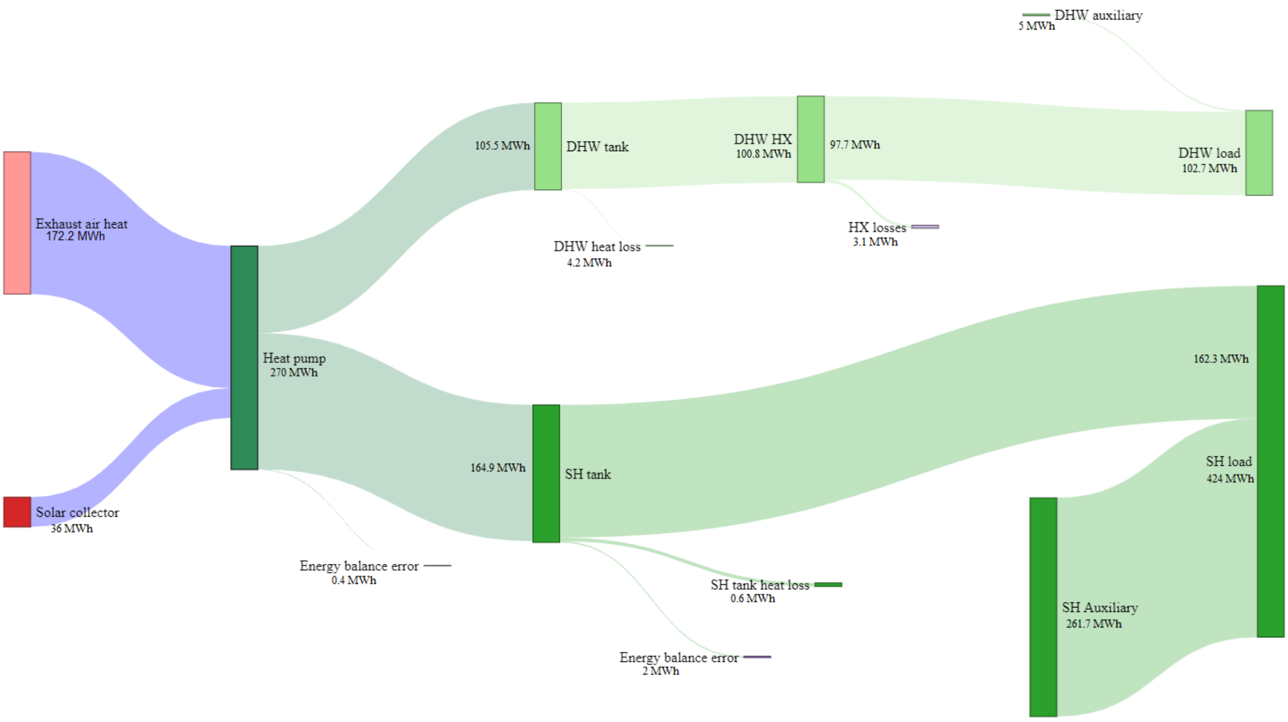

Figure 26. Sankey diagram to represent various energy flows in the system

2.3.3 Opportunities and barriers

Table 6. SWOT analysis of Solar assisted exhaust air heat pump system

	Strengths	Weaknesses	Opportunities	Threats
	*Easy integration of transpired collectors with EAHP in series arrangement. *Improvement in overall system performance.	* Relatively small increase in EAHP performance due to availability of exhaust air from ventilation. *Additional space needed for the installation of the transpired solar thermal collectors.	*Solar collectors in combination with Air source heat pump can be used in addition to EAHP system. This will decrease the auxiliary heating requirement for overall energy systems.	*Unfavourable façade exposure and external shading as well as unfavourable weather conditions can severely limit the benefit from transpired solar thermal collectors *To achieve a higher utilisation ratio for collectors, air storage should be explored, and is expensive compared to water storage systems.

3. Electricity generation system concepts

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3.1 Solar window package

3.1.1 System description

The solar window package (ER4) solution provides a set of options to integrate additional functions in a standard window mono-block for residential buildings, such as electricity generation, dynamic and automated shading and ventilation of the adjacent space. The aim is to develop a high-quality alternative to the standard window replacement that can offer several advantages ranging from improved indoor environmental quality to the minimization of the extra cost and construction works.

In the Energy Matching project, the window block is designed as system integrator that possibly embed: (i) a new shading systems; (ii) a decentralized ventilation machine and (iii) a PV element, as drafted in Figure 27.

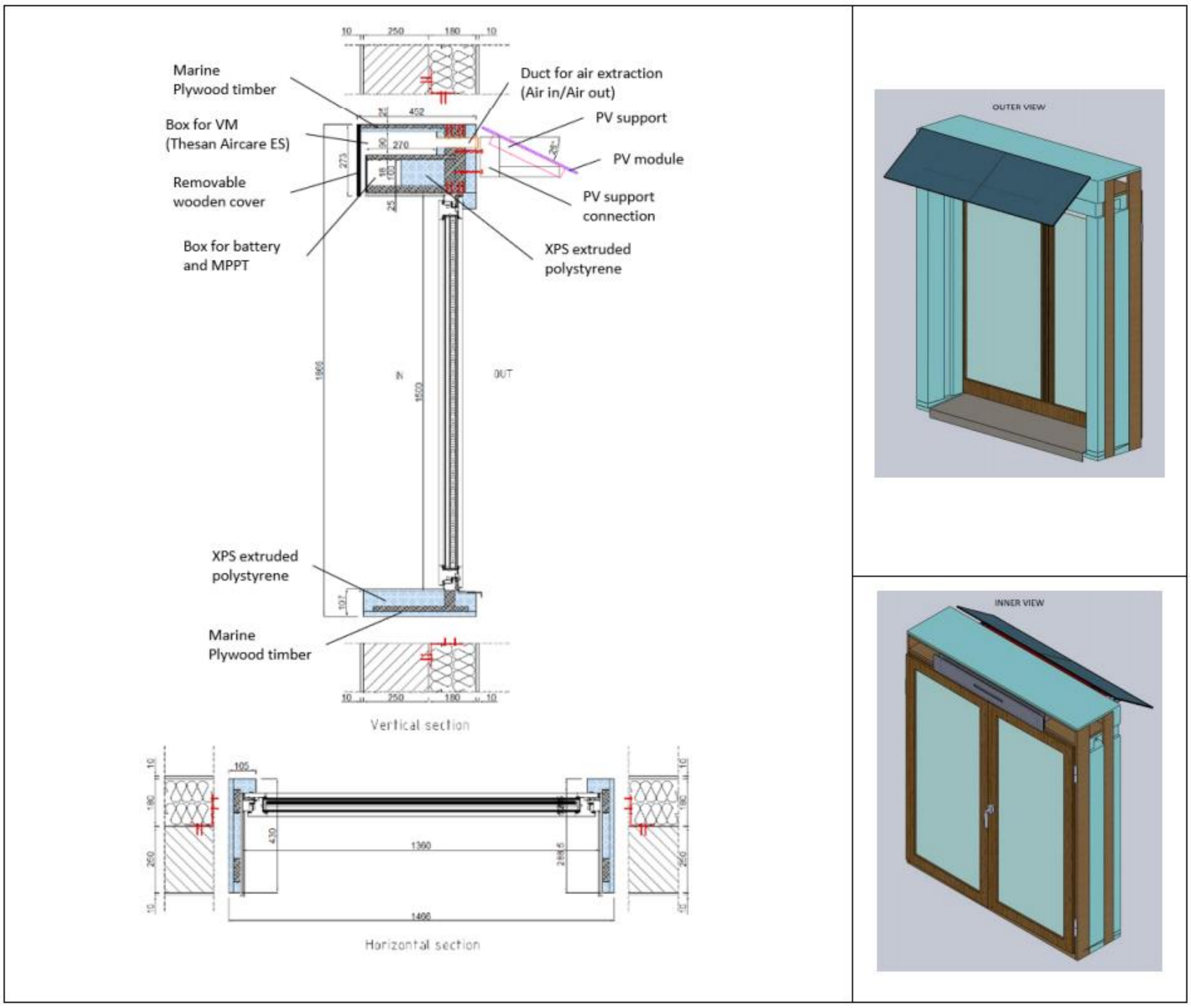


Figure 27. Solar window package mock-up with BIPV overhang (Source: Eurofinestra and Eurac)

The first two components are key elements in a comfortable and energy efficient building. On the one side, an optimal management of the solar gains can effectively reduce the thermal load of the building and mitigate the risk of overheating. On the other, the integration of a decentralized ventilation machine opens the possibility to increase indoor environmental comfort while minimizing the impact of renovation works on building occupants, avoiding the use of air ducts. Moreover, the addition of a PV module in the window block system tackles the topic of local generation of renewable energy, here exploited to power the ventilation machine. More in detail, Energy Matching focuses on the advantages of electrical self-consumption, also leveraging on the use of decentralized storage (e.g. battery). This also allows to install a multifunctional window block system without requiring electrical wiring works to be performed inside the building.

Overall, the main drivers of the design process of the window monoblock are:

- adaptability to changing indoor and outdoor conditions;
- off-site fabrication, with most of the assembly work carried out in a manufacturing environment, maximizing fabrication precision;
- minimized impact on building occupants, thanks to the reduction of on-site works and most of the installation related operations carried out on the outside of the building;
- timely matching between energy production from renewable energy sources (RES) and energy consumption, thanks to the optimization of system production and on-site self-consumption;
- design flexibility and modularity, to guarantee easy integration and boost replicability of the technological concept.

3.1.2 Main results

The application of solar window blocks (SWB) is studied in the Italian demonstration case of Energy Matching. All windows integrate PV panels and are configured to be off-grid, with possibility to be connected to the grid (as back-up only, in case the off-grid system will fail) after the end of the project. A performance-based approach was applied, evaluating building-physics related aspects and Indoor Air Quality (IAQ) on one side, electrical production and energy autonomy of the overall system on the other.

The simulation performed aimed at evaluating the hourly matching between the SWB PV production and the associated ventilation consumption profiles in the Italian demonstration case application (Figure 28). The results are provided as percentage of ventilation working hours (i.e. hours when the ventilation is effectively activated by the PV-battery system respect to the number of hours when the ventilation unit shall be activated according to the scheduled fan speed profile) and expected discomfort hours (i.e. percentage of occupied hours when CO_2 concentration is greater than 1750 ppm). The simulations show that out of the 39 SWB installed in the Italian demo case, 25 SWB guarantee at least 90% of the ventilation working hours, 5 SWB guarantee at least 80%, 6 SWB guarantee at least the 70%, only 2 SWB guarantee at least the 60%. Despite the expected lower number of working hours of the ventilation unit compared to the scheduled ones, the percentage of expected discomfort hours over the year in the worst cases (60%of working hours) is only 6% in the living room and 10% in the double bedroom (as shown in Figure 29).

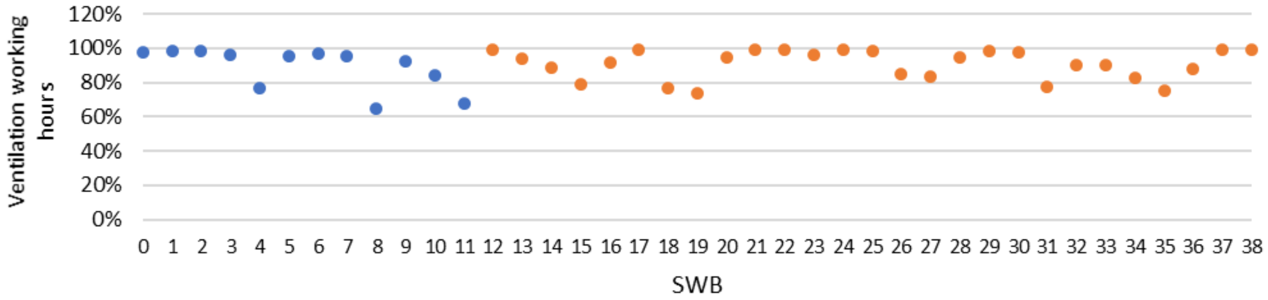


Figure 28. Results of the simulations performed on the 39 SWB to be installed in the Italian demo. 12 SWB are integrated in the living rooms (in blue) and 27 SWB are integrated in the bedrooms (in orange). Ventilation working hours are calculated considering the hours that the ventilation effectively works (thanks to the photovoltaic production) respect to due working hours based on the related profile.

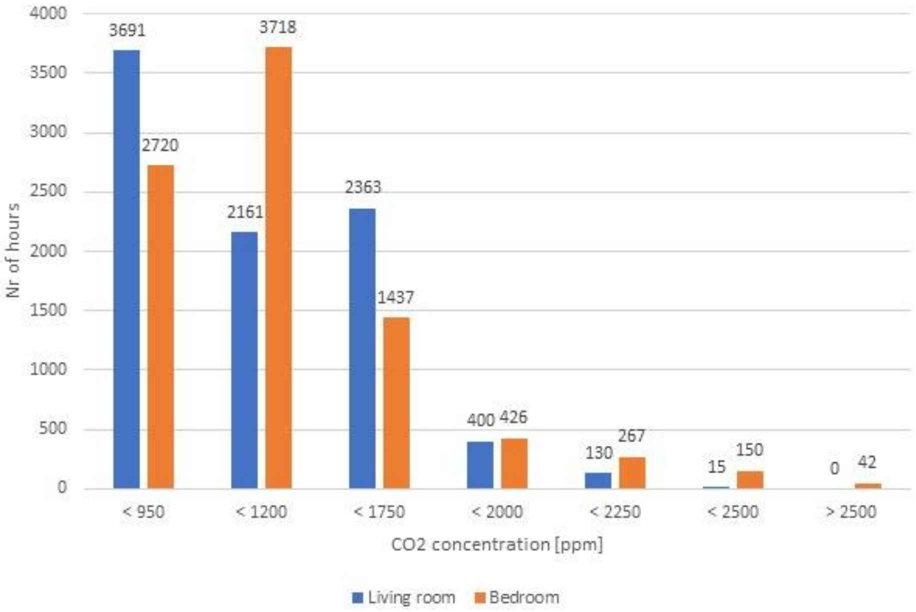


Figure 29. Evaluation of CO_2 concentration for the analysed living room and bedroom

3.1.3 Opportunities and barriers

Take an example of the Italian demo application, the ventilation unit control is demanded to the standard control set by the ventilation unit provider. Following general recommendations are provided in order to optimize ventilation control:

- In case the ventilation unit is installed in the living room: avoid activation of ventilation during the hottest hours of the day in the cooling season and during the coldest hours of the day in the winter season; instead increase ventilation rates during coldest hours in the cooling season and during hottest hours in the heating season; adjust fan speed based on the number of occupants of the room.
- In case the ventilation unit is installed in the living room: set constant fan speed over the night to avoid noise discomfort and adjust fan speed based on the number of occupants of the room.

Further developments on control strategies can potentially improve the performance of the SWB taking into account the battery state of charge:

- For bedroom applications, the ventilation unit could set its fan speed depending on the battery state of charge at the beginning of the night in order to ensure a constant fan speed for all over the night. As example, if at the beginning of the night the battery charge state is lower than 60%, corresponding to a capacity of 58 Wh, then the fan speed can be set at 2 (power input 5.8 W, airflow 20 m3/hr) in order to maintain a constant flow rate and a constant noise level for the next 8 hours.

- Ventilation unit can be activated when battery is charged and there is potential for free-cooling.

Strengths, weaknesses, opportunities, and threats of the SWB application are presented in Table 7.

Table 7. SWOT analysis of solar window package

Strengths	Weaknesses	Opportunities	Threats
SWB system is characterized by a medium level of prefabrication that allows to ease the installation process and to minimize the impact on building occupants. no need for grid connection. Able to ensure acceptable ventilation levels under standard use conditions and at the climate conditions analyzed	Ventilation unit control depends on user settings SWB configuration need to be defined through the design process taking into account window position, climate and potential shadings from surrounding environment.	If properly designed, the system can be totally self-sufficient High replicability of the solution since no ductwork is needed and can be easily installed Advanced control strategies based on the battery state of charge can improve its performance both in terms of self-sufficiency, free-cooling and IAQ	Intermittent functioning of the ventilation unit because of no power output can be annoying for building occupants and they might shut off the ventilation unit

3.2 PV-driven heat pump

3.2.1 System description

PV-driven heat pump is part pf ER6 – ‘Renewable harvesting package to heat and ventilate’ solution. Figure 30 shows the layout of the presented energy concept. This is the same basic system described in section 2.2, with the additional capability of advanced controls that can maximize the use of the PV electricity in the building (or cluster of buildings in the following section). The key additional innovative elements are:

- EnergyHub: that is a multifunctional power manager (see section 1.3) that in this concept is used for managing the PV power (string optimizer), battery charge control and grid connection.

- DC driven heat pump, where the variable frequency inverter of the heat pump is connected directly to the DC-grid of the EnergyHub (see section 1.1).
- Extra water storage to store excess PV electricity in the form of heat. This heat can then be supplied to the thermal loads. In this example the thermal loads are both in the form of heat, but in principle cold storage is also possible for summer operation. Heat can also be stored in the building itself by having temporary slightly higher room set point temperature. Kensby [6] has already studied active use of building thermal mass in district heating systems for demand management and found that ~0.1 $kWh/m^2_{heated\ area}$ can be stored without varying the indoor temperature by more than ± 0.5 °C. The concept is implemented and demonstrated on a relatively large scale in Gothenburg, Sweden, but is not used in the demonstration sites.
- It is also possible to consider advanced control of EnergyHub and heat pump using electricity price as well as weather forecasts, where there is economic benefit.

At present, thermal storage is more cost-effective than electrical storage for a coupling of PV and heat pump [8], but the price of electrical storage is decreasing rapidly and this might change with time and will be different in different electricity markets. In addition, the EnergyHub with battery can provide several other grid services such as peak shaving, which will increase the cost-effectiveness of having a battery, but this use will be a competitor to use of the battery for storage of PV electricity.

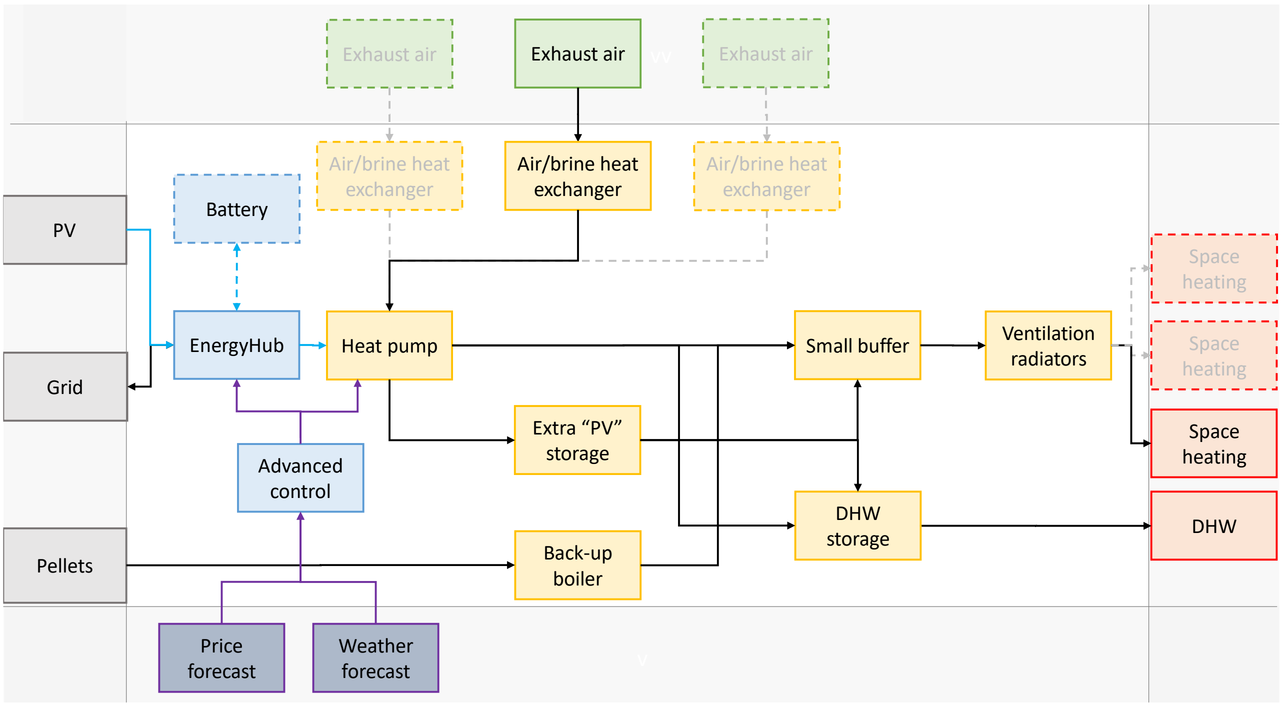


Figure 30. Example layout of centralized exhaust air heat pump with extra electrical and thermal storage for locally harvested electricity (PV).

With the additional elements described, the complete system can store the excess PV electricity at times when the feed-in tariff is low (based on price forecast) as either electricity (in the battery) or heat in the water store or in the building itself (not shown in the figure). The controller can also use the thermal and electrical storage if the purchase tariff is predicted to increase significantly in the next few hours, thus buying electricity at a low price instead of a higher one. These operation modes are in addition to the standard ones described in section 2.2. The basic principle can be applied to other electrically based systems with PV arrays – it is not restricted to exhaust air heat pumps.

The excess of PV power production can also be stored in form of heat with the use of a hot water storage and a heat pump rather than in electrical batteries.. In this case, the excess of electricity is used to power the heat pump for producing heat, which is stored in a separate hot water tank. The stored heat can only be used for

DHW purposes in the chosen system design. The algorithm varies the speed (and thus the heating capacity) of the heat pump in order to match the total electricity load with the PV supply. If there is a battery in the system, the utilization of thermal storage is prioritized. The battery is only used when the thermal storage is fully charged.

The role of the hot water storage is to increase the self-consumption by enabling some part of the electricity to be used in a non-contemporaneous way. If the EnergyMatching tool (in WP2) is used for optimizing the size and placement of the PV, an iterative series of optimizations is foreseen as a 'ping-pong' process due to the fact that the tool does not include thermal storage for storing excess PV in the form of heat. The ability of transforming the excess PV electricity in thermal energy generates an increase of the electric demand during the times of over-production. This encourages the next optimization process to install a higher capacity restoring the situation of overproduction in some hour of the year (HOY). The process is then repeated with the aim to exploit the over-production, nevertheless the average temperature of the storage is higher this time as the thermal need is limited, so the increase in electric demand is minor. When this optimization process does not yield to any increase of PV capacity, it is assumed that the process as converged to the optimal solution.

3.2.2 Main results

A PV driven heat pump system with storage for space heating is simulated. Rule based control algorithms that can easily be implemented into modern heat pump controllers are developed with the aim to minimize final energy and maximize self-consumption by using the thermal storage of the building, the hot water tank and an electrical storage. The role of the storage is to increase the self-consumption by overcoming the mismatch between PV production and loads. As stated previously, an iterative series of optimizations can be conducted together with EnergyMatching tool (ER2) to better exploit the excess of PV electricity production. Taking the Swedish demo case as an example, a second iteration generates a large increase in the optimal PV capacity compared to the baseload scenario (+21%): this is not due to the increase in electric demand (the overall demand is basically unaltered as the increase during the central hours is compensated by a reduction in the evening), but it is due to the improved matching of the demand with PV production. The electric demand resulting from the use of excess of PV electricity production presents a bump during the central hours of the day. This feature makes it easier for the PV to match the electric demand and allows the optimization algorithm to install a larger capacity of PV. The main result is the reduction of the residual electric demand (i.e. the part that cannot be covered by the PV system + thermal storage) estimated to be -6.8% reduction over the whole process, leading to a better contemporaneity between production and consumption [7].

3.2.3 Opportunities and barriers

The main opportunities and barriers to the implementation of this energy concept are listed in Table 8.

Table 8. SWOT analysis of PV-driven heat pump system

Strengths	Weaknesses	Opportunities	Threats
*Maximizes use of locally harvested PV electricity *Flexible system with optional battery storage that can be adapted to	*Thermal storage in water requires space in technical room *Thermal storage in building thermal mass requires possibility to adjust set temperature in the flats as	*Cost-effective use of PV excess electricity, meaning that larger PV fields can installed and still be profitable	*Ownership structures can make it difficult for implementing centralized HVAC solutions

	the boundary conditions for a given case	well as tenants approval to do so. However, this is an option that is not essential in the concept *Relatively complex system that requires advanced control and access to forecast services. Simpler control algorithms can however be used without these services	*Possible to connect with DC grid to involve several buildings *System would also be possible to adapt to more active demand side management. At present this management is indirect via the electricity price *A battery storage can be used to provide other services to the grid owner and utilities	*User changes of set points could decrease the benefits of thermal storage in the building mass

3.3 District DC Grid

3.3.1 System description

District DC grid is part pf ER7 – ‘Building and district energy harvesting management system’ solution. The EnergyHub District DC grid system concept shown in Figure 31 is able to maximize the use of the locally produced electricity (e.g., PV, storage and small scale wind) for use within the district. These DC micro-grid distribution systems are becoming more attractive in comparison to traditional AC distribution systems thanks to their ability to be easily integrated with several types of renewable resources, energy storage systems, electrical vehicles (EV) and other DC based loads. Moreover, since only AC can be delivered or consumed, special inverters (EnergyHub units) are required to interconnect the “internal” DC power with the “external” AC grid (see section 1.4).

Specifically, the PowerShare technology uses a 760 VDC nanogrid to feed energy from one or more common PV installations to multiple users. A local bidirectional inverter at each user, controls the flow of energy between the DC nanogrid and the user. In addition to sharing PV installations the technology can also be used to share a central energy storage among multiple users. The system brings a significant increase in PV self-consumption at a fraction of the cost of batteries. Further, load peaks at one user, for example from EV charging, can be distributed among other users to reduce peak load drawn from the public AC grid.

The today dominating solution for increasing PV self-consumption is the use of energy storage systems that come at a very high cost. The use of a DC nanogrid with multiple inverters enables a much more cost effective way of increasing PV self-consumption by directing energy to the user that have consumption at any given time. Another unique application is when the peak load from EV charging is higher than what the feeder cable to the building can deliver or the subscribed power allows, then part of the power can come from your neighbour rather than from a costly battery.

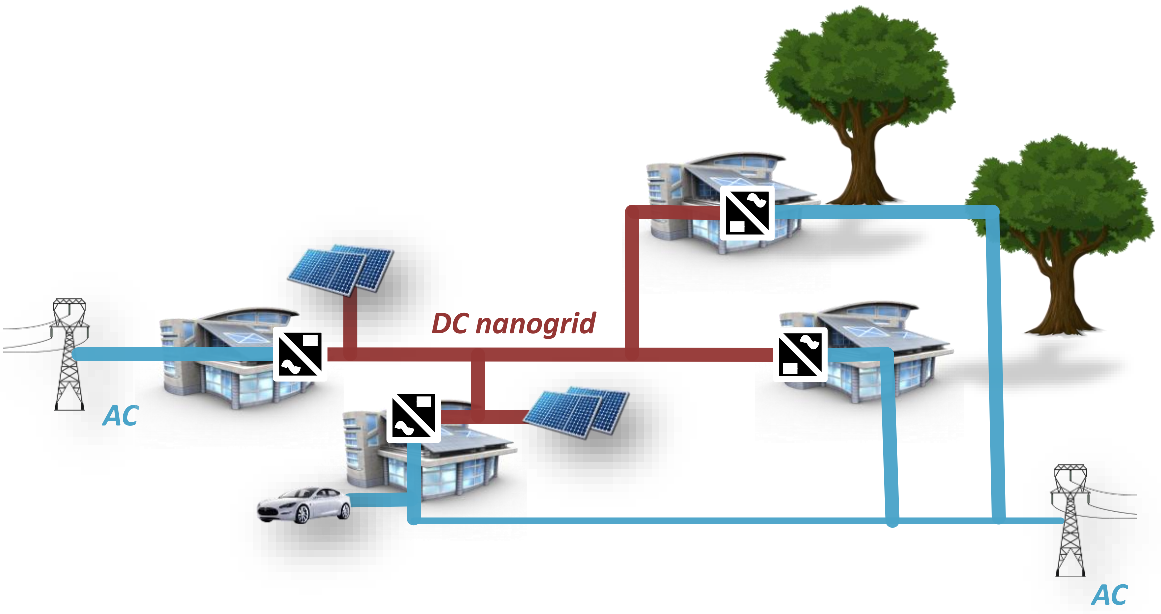
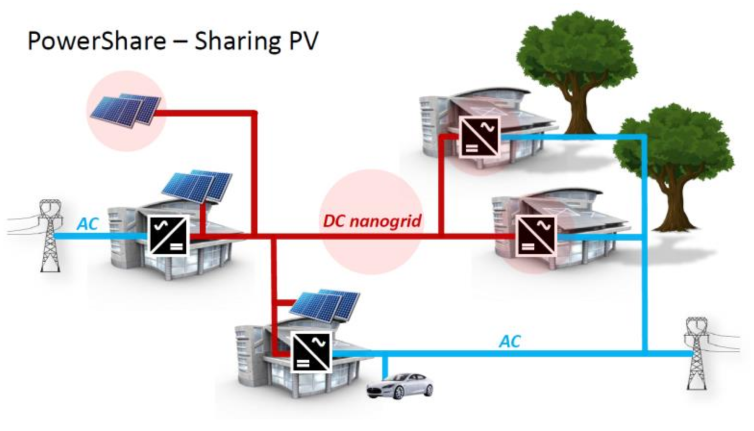
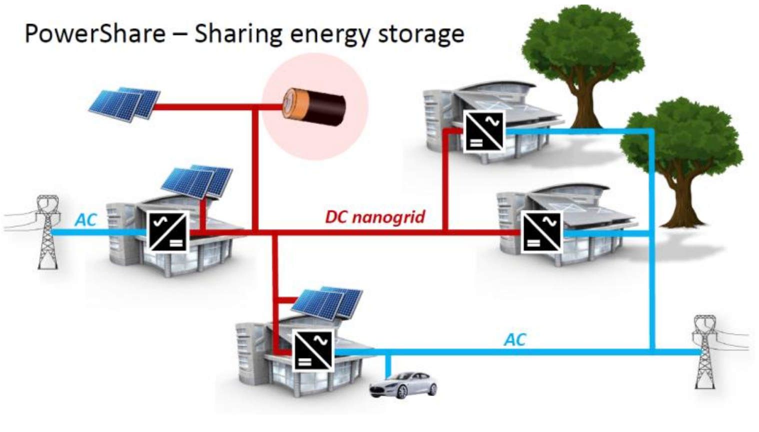


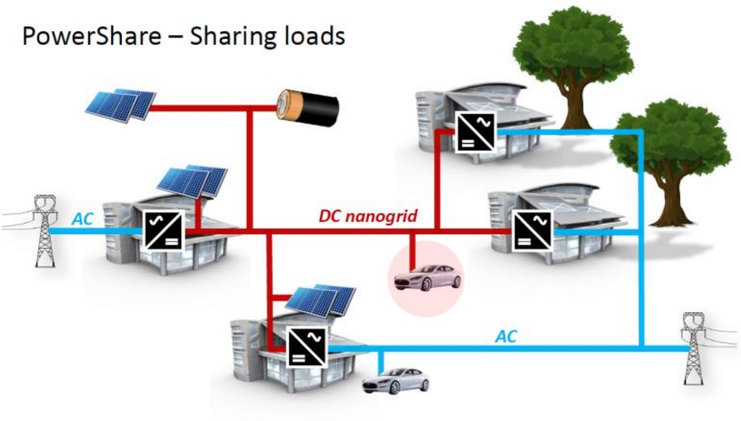
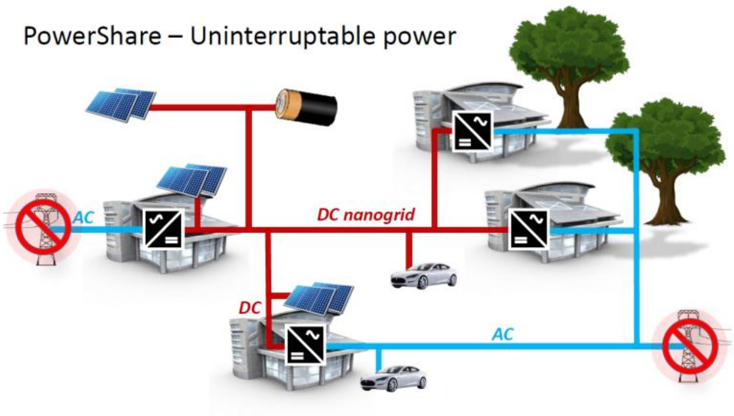
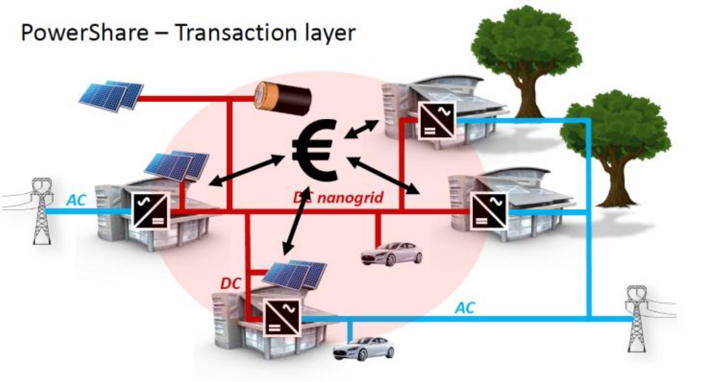
Figure 31. District DC nanogrid

3.3.2 Main result and possible applications

A number of applications of the PowerShare Technology is listed in Table 9.

Table 9. Use cases of PowerShare Technology

Sharing PV By sharing a PV installation, a property owner can utilize the most suitable space for PV but transfer the energy to the building with the highest demand, thus increasing self-consumption.	
Sharing energy storage By utilizing the PowerShare technology and sharing an energy storage, the capacity of the energy storage can be reduced compared to that each building were to install its own energy storage.	

Sharing loads By sharing the loads the AC grid subscriptions does not have to be increased and/or the system will be able to support more DC loads e.g. EV charging stations.	
Uninterruptable power during power-outage Use shared resources to maintain power during a power-outage.	
Transaction layer to support sharing economy services Monitor energy flow to be able to build economy services on the PowerShare Technology.	

3.4 Optimised system control for building cluster

3.4.1 Control method description

Optimised system control for building cluster is part pf ER7 – 'Building and district energy harvesting management system' solution. To improve the performances at the building cluster level, a top-down RES building district control is developed in this project, and the overall concept is given in Figure 32. Figure 33 presents the flowchart of the developed top-down coordinated control with EV considered [8]. The aim of the coordinated control is to manage the operation of energy storage (installed in each single building) and the EVs in individual buildings, to achieve the optimal cluster-level performances. The coordinated control consists of four steps described below and illustrated in Figure 32 and Figure 33.

- In Step 1, all buildings of the cluster are considered as a 'representative' building, and the electrical demand, renewable energy generation and load shifting capacity of the 'representative' building are predicted, i.e. its electrical demand/renewable generation/demand shifting capacity equals the aggregated demand/ generation/capacity of all buildings inside the cluster.
- In Step 2, the operation of the 'representative' building and EV charging rates are optimized using genetic algorithm (GA). The performance of the 'representative' building, obtained by simultaneous optimization of the building and EV operation, is considered to be the best performances that the building group can achieve.
- In Step 3, the operation of each single building inside the building group is coordinated using non-linear programming (*NLP*) based on the 'representative' building's operation obtained from Step 2.
- In Step 4, the performances of the proposed coordinated control are compared with two existing controls, including a conventional individual control (Scenario 1), which does not enable renewable sharing and charge the EVs immediately after being parked, and an existing coordinated control (Scenario 2), which enables full renewable energy sharing but also charges the EVs immediately after being parked. The details of each step are introduced below.

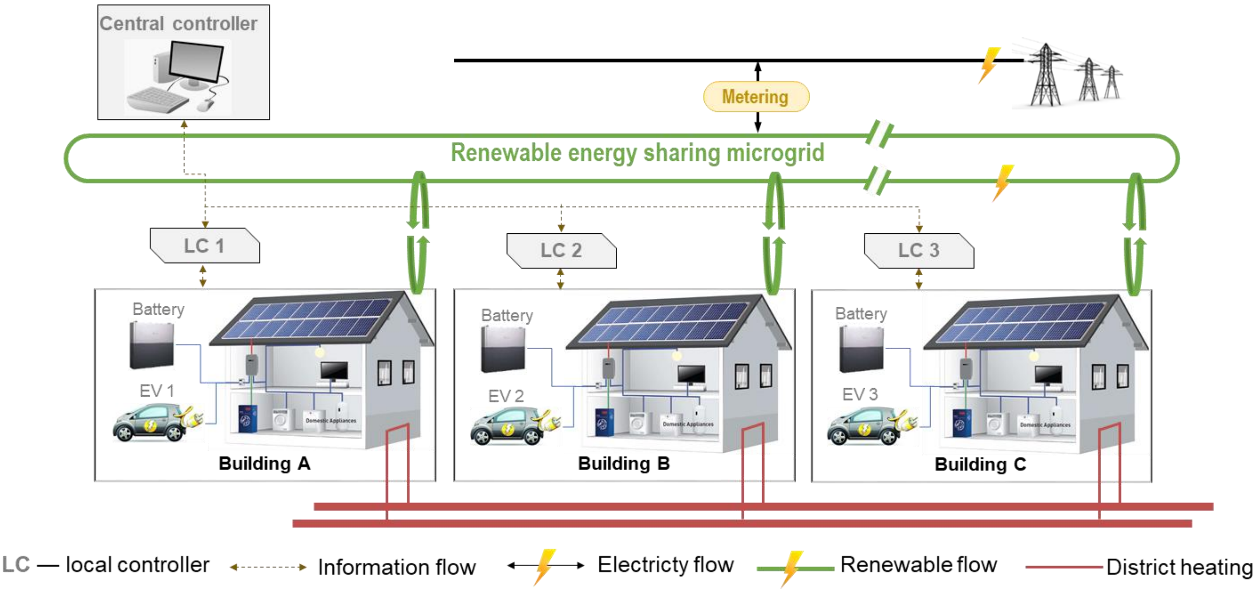


Figure 32. Schematics of electricity energy sharing among buildings in a cluster

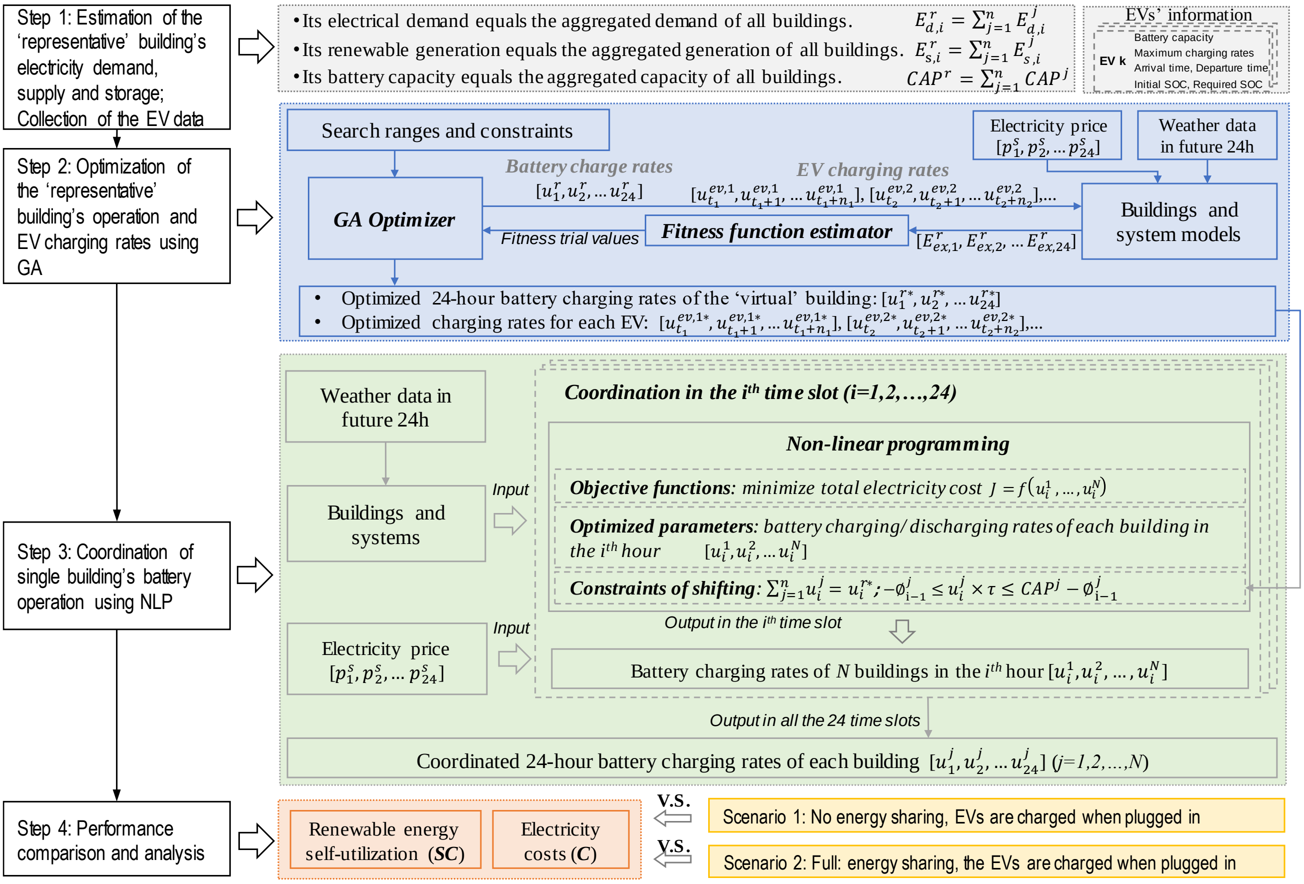


Figure 33. Flowchart of the top-down coordinated control to improve energy performance for a building cluster with energy storage, EVs, and energy sharing

3.4.2 Main results

The Swedish demonstration site is used as case study to evaluate the benefits of advanced control strategies described above by means of numerical simulation. A typical summer week is selected to validate the developed coordinated controls. The weather data of Ludvika is used for modelling the local renewable generations. The advanced control is compared with two existing scenarios: Scenario 1-individual building control with no energy sharing, and no smart EV charging; Scenario 2-building cluster control with full energy sharing, but no smart charging. It is assumed that in each building is installed an electrical battery with capacity of 20 kW·h and a maximum charging/ discharging rates of 6 kW. The price of purchasing electricity from the power grid is set as 0.16 €/(kW·h). Considering the negative impacts on the grid stability and safety, the feed-in-tariff is set as 0.05 €/(kW·h), which is lower than price of electricity purchase. The price of electricity trading in the building cluster is set as 0.1 €/(kW·h). Such price setting will provide incentives for energy sharing within the building cluster, i.e. the building owners can earn more by selling their excessive renewable energy to the building cluster than sell to the power grid, and vice versa.

Figure 34 depicts the electricity energy flow of the subsystems (i.e. electrical demands, renewable generation, EV demands and battery charging/discharging) in each building in the first day of the selected week for the three different scenarios. It also shows the individual building's energy exchange with the building cluster (i.e. the other buildings) and with the power grid. A positive value of energy flow indicates energy demand, while a negative value indicates energy supply. For the power grid/building cluster, a positive energy flow indicates buildings export electricity to the power grid/building cluster, while a negative energy flow indicates buildings import electricity from the power grid/building cluster.

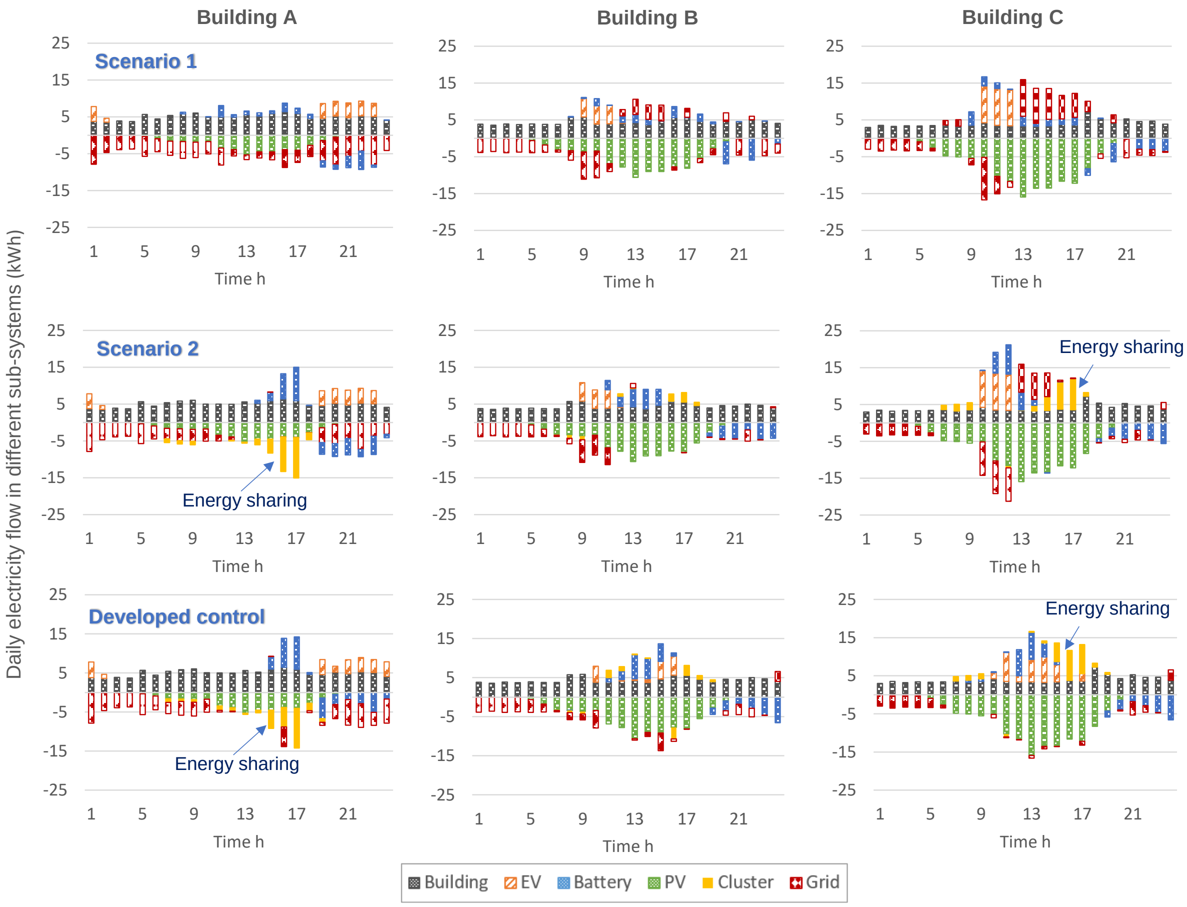


Figure 34. Detailed electricity flow (of building, PV systems, battery and EV) in the individual building in each scenario in the first day of the selected week

Figure 35 indicates the electricity energy flow of the building cluster (i.e. electricity demand), aggregated PV production, power grid, aggregated battery and three EVs in the first day of the selected week for the three different scenarios. The aggregated energy exchanges within the building cluster become zero in the aggregated level, since the amount of purchased electricity from the building cluster compensates with the amount of electricity sold to the building cluster. In the period 9:00~12:00, for Scenario 1 and Scenario 2, large electricity demand occurs, as EV 2 and EV 3 are charged immediately after being plugged in. Unfortunately, the renewable energy generation is not sufficient in this period to meet the large demands. As a result, a large amount of grid electricity is purchased by the building cluster. In Scenario 3, as EV 2 and EV 3 can be flexibly charged in any timeslot during the parking period, the controllers set relatively small EV charging rates in this period. Consequently, the amount of grid power purchase is significantly reduced in the developed control. In the period 14:00~17:00 (see the grey box), for Scenario 1, since there is no collaboration among buildings, only a small part of the surplus renewable energy is kept onsite, while a large part of the surplus renewables is exported to the power grid at a low price. In Scenario 2, contributed by the energy sharing within building cluster, more renewable energy can be stored in the battery. After the batteries in the building cluster all being fully charged, a small amount of surplus of renewable energy is still exported to the power grid. Scenario 2 has better performance compared with Scenario 1. Since the batteries of EV 2 and EV 3 have already been fully charged in the period 9:00~12:00, there is no energy flow for them in the period 14:00~17:00. In the developed control, considering the large renewable energy production in this period, the controller shifts the charging load of EV 2 and EV 3 to this period. Part of the surplus renewable generation is stored in the building battery and part of the surplus renewables is used to supply the EV load. As a result, exporting renewable energy to the power grid is completely avoided. This can effectively improve the renewable energy self-consumption rate of the building cluster.

To sum up, Scenario 2 performs better than Scenario 1 since the energy sharing enables to keep more renewable energy on-site. Scenario 3 performs even better than Scenario 2, as the controller shifts EV charging loads to periods with large renewable production (and thus helps to keep more renewable energy used on-site in case the batteries have been fully charged).

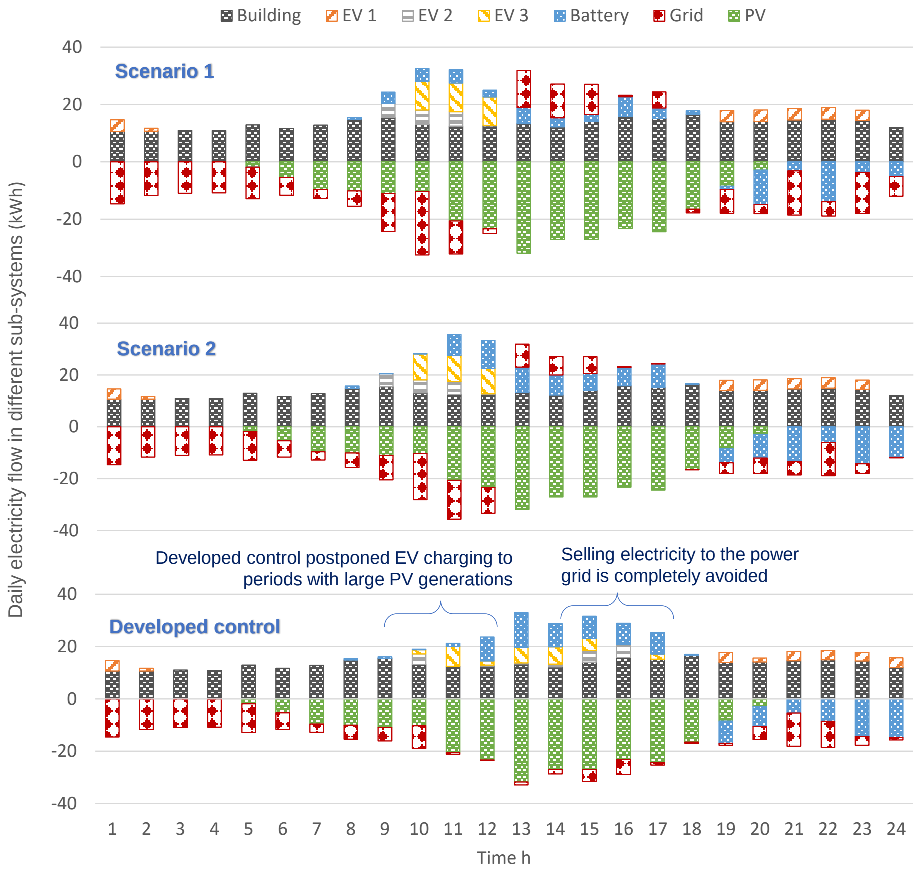


Figure 35. Detailed energy flow (of building, PV systems, battery and three EVs) in the building cluster in each scenario in the first day of the selected week

3.4.3 Opportunities and barriers

The advanced control for building cluster can effectively help improving the overall renewable energy self-consumption by simply enabling energy sharing. Such increase of renewable energy usage will not only contribute to the PV panel paybacks, but also reduce the impact on the power grid. Although these results are very encouraging, several barriers (such as the legislation on peer-to-peer energy trading or the lack of valid business models) must still be overcome to proceed with practical implementations.

4. Energy concept designs for three demo cases

4.1 Swedish demo case

4.1.1 Demo case information

The studied building cluster is located in Sunnansjö, Ludvika, Dalarna region, Sweden. This demo site is a multifamily dwelling unit made of three buildings built in 1970/1973, as shown in Figure 36. The cluster (three buildings) includes 48 apartments over three floors, and most of the apartment have one or two bedrooms. The total façade surface gross area of the complex is 2,146 m^2, the total roof surface gross area is 1,750 m^2,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°768766

and the total heated area is 3861 m^2. The energy consumption of the cluster is 165 kW×h/(m^2×year), including operational electricity but not including electricity used in the flats for appliances and lighting. The space heating and DHW are supplied by a boiler with one-pipe circulation. There is no need for cooling. These buildings will be improved by a series of renovation plans including installation of PV, thermal energy storage, DC micro grid, EVs and heat pump systems.

Figure 36. Three buildings in the cluster for renovation in Ludivika, Sweden

4.1.2 Retrofit intervention

With the purpose of improving the overall energy performance and reducing carbon emissions of the building cluster, the following interventions are being applied in renovating this building cluster. First, a centralized heat pump using exhaust air and ground as heat sources will be used for supplying the heating and hot water for all the three buildings. All the exhaust air in each building will be ducted to a heat exchanger unit, in which the waste heat will be recovered and then delivered to the centralized heat pump via a brine loop. A back-up pellet boiler is utilized to accommodate the peak heating needs. The PV can be installed on the roof and façades of the buildings. The PV energy is first used to power the electrical facilities in the buildings (e.g. fans, pumps, lighting, EV demands). After this part of electrical load is met, the remaining PV energy is considered as excess PV energy. A hot water storage is planned to store the excess PV energy in the form of heat, where the excess PV electricity power is transmitted to the heat pump to produce heating energy, and the produced heat is stored as the hot water. All electricity in the buildings, including that in the flats, as well as that supplied to the EV's is managed by one Energy Hub in each building, connected together via a DC micro grid. The DC sources (i.e. PV) and sinks (i.e. EVs and variable speed heat pump compressor) as well as batteries, if present, are connected directly to the DC micro grid. The overall energy concepts (the advanced techniques used in the building cluster renovation for improving the overall energy performance) of the renovation plans are presented in Figure 30 and Table 10.

Table 10. Overall energy concepts for Swedish demo case

	Intervention	
	1	Centralised heating and hot water for all three buildings supplied by one centralised heat pump using exhaust air as heat source.
	2	All exhaust air in each building (incl. kitchen & bathroom) is ducted to a heat recovery heat exchanger unit in the attic of each building
	3	Use a back-up pellet boiler
	4	Change to 2-pipe heat distribution system with ventilation radiators in all buildings
	5	Use extra hot water storage to store excess PV energy in the form of heat

6	Roof PV on two of buildings, possibly PV on facades of two buildings
7	Apply Ferroamp energy hubs in buildings linked by DC grid
8	A new culvert will be made between buildings containing brine loop, DHW, DHWC, space heating pipes, cold water, DC link (Ferroamp) and computer cables.

4.1.3 Preliminary evaluation of the energy demand pre- and post- retrofit

TRNSYS 18 is used to simulate the building and energy systems in a two stage process where an hourly space heating load file is generated by a building model in the first stage that is then used as input in the second stage to the HVAC system model. In the first stage, all three buildings are modelled in one Type 56. A 3-D model built in the tool SketchUp is used to generate the geometry of the buildings, as shown in Figure 37. The model is then converted into the non-geometric mode in order to have a faster simulation time, and material properties based on the real building are added. Ground coupling is done using a simplified approach with Type77 providing the ground temperature to which heat losses are calculated. The occupancy, electricity and DHW load profiles for the flats are derived by a stochastic model [9] and the annual electricity usage has been calibrated to the measured data. The internal gains due to operational electricity are based on the measured values and assume 100% is converted to heat. The simulation model is then calibrated with the available measured data in order to achieve acceptable accuracy.

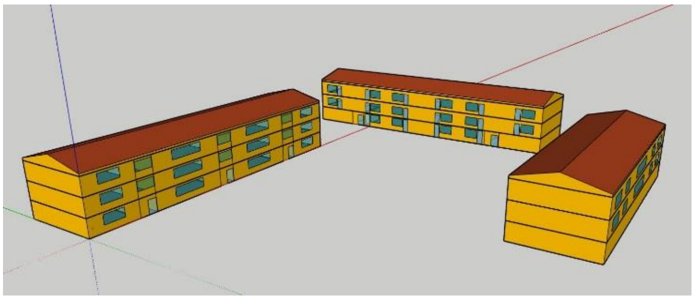


Figure 37. SketchUp model of three buildings in Swedish demo case

The HVAC system model is a simplified model of the proposed HVAC system, as shown by the TRNSYS model in Figure 38. Similarly, only one exhaust air heat exchanger is modelled using Type508b as brine source to the heat pump, using the total ventilation flow rate for the district of 1460 l/s as input. The heat pump is modelled using Type1927, which uses a performance map with source and load inlet temperatures, source flow rate as well as compressor frequency as independent variables. A detailed performance map covering the range of operating conditions is provided by the Nibe that is used in the system. The heat pump has a nominal heating capacity of 45 kW with a COP of 3.82 at B0W35 and 102 Hz compressor frequency. The space heat is controlled using a heating curve for a heating system with design temperatures of 55/45 °C at a design ambient temperature of -23 °C. The heat pump frequency is controlled using a PID controller to supply the current flow temperature according to the space heating curve. If the maximum frequency does not give enough heat, a Type 6 auxiliary heater with 200 kW maximum heating rate adds heat in order to generate the required flow temperature. This auxiliary heater, representing the pellet boiler of the real systems, is thus only used for space heating, and supplies only as much heat as required to match the space heating load. A small buffer store of 370 litres is located in series between the heat pump and the auxiliary heater. The DHW of 2.5 m^3 and the extra store for excess PV in the form of heat are further modelled with one Type 534 each, using five zones and connections at the top and bottom. The store volume is 3.5 m^3 for the case study as presented in section 4.4.

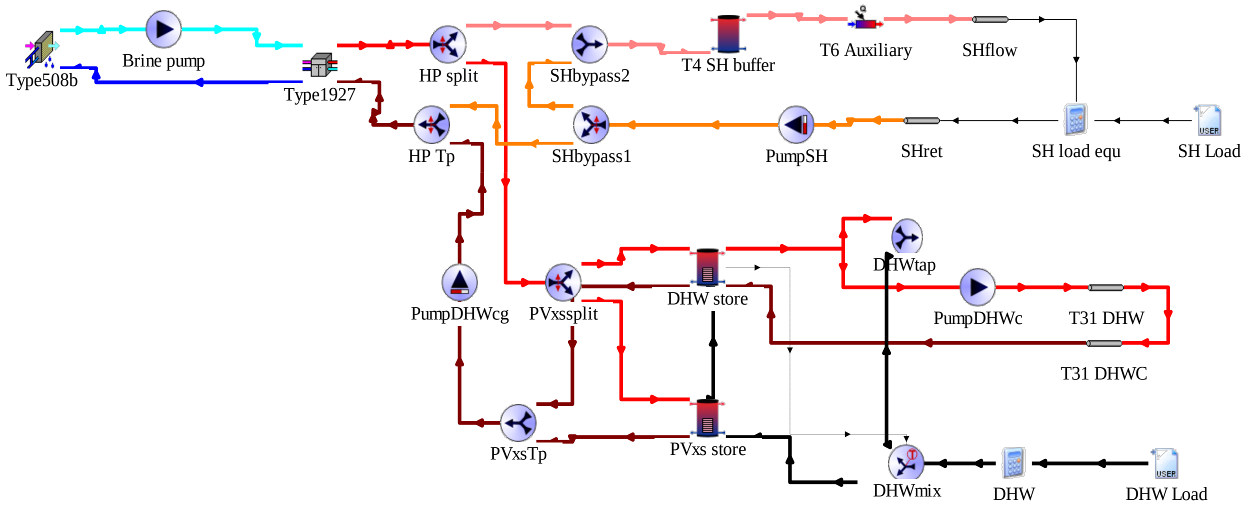


Figure 38. HVAC system modelling in TRNSYS for Swedish demo case

The total thermal load of the building consists of space heating (SH) and DHW. The annual thermal energy demand for the building cluster is about 526.7 MWh. The annual SH and DHW demands are 424 MWh and 102.7 MWh respectively. The area-specific SH and DHW demand are 109.8 kWh/m^2 and 26.6 kWh/m^2 respectively. The frequency variation in thermal demand is shown in Figure 39. It can be seen that the peak demand is up to 198 kW, and occurs only for a few hours in a year. However, the heating capacity of the auxiliary heating system is limited by the peak thermal demand of buildings. The annual average thermal demand for building clusters is 59.4 kW. The simulation results are further calibrated with real measurements. The monthly variation in aggregated thermal demand is shown in Figure 23, which illustrates that nearly 80 % of the total demand is for SH and the rest 20 % is due to DHW. The seasonal variation in the SH demand is higher and most of the demand occurs in months with a low ambient temperature. On the contrary, the DHW demand has a small seasonal variation, as the requirement for hot water is consistent over the year.

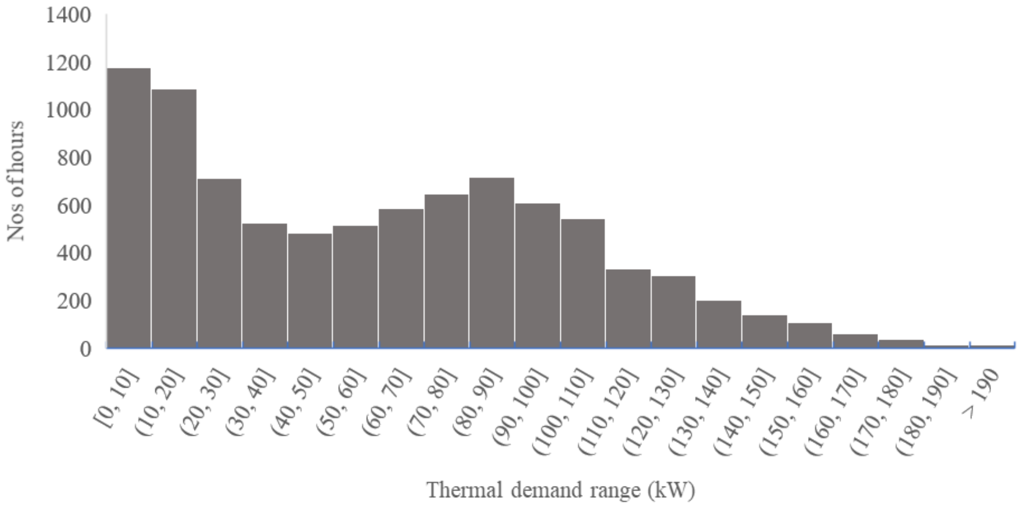


Figure 39. Frequency distribution of the thermal demand in Sweden demo case

The overall energy benefits from applying the energy concept are summarized as: (1) heat pump covers 56% heat demand, and (2) bought energy is reduced by 42%. Figure 40 shows the main result.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N°768766

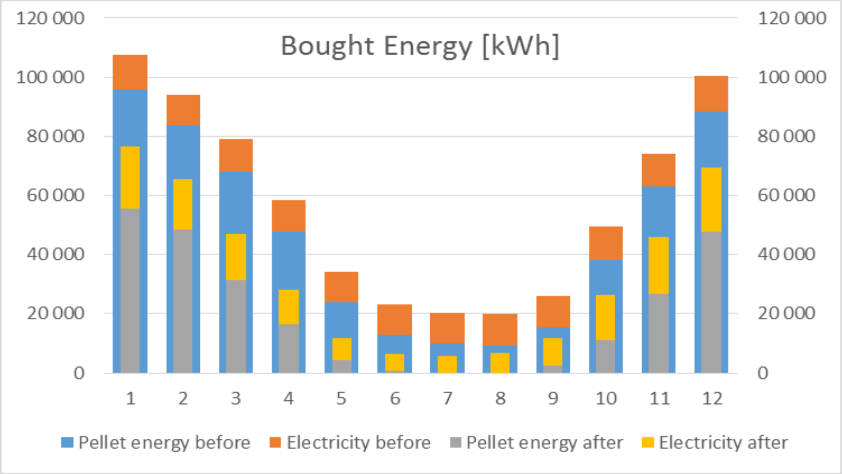


Figure 40. Overall energy benefits from applying the energy concept in Swedish demo case

4.2 Italian demo case

4.2.1 Demo case information

The studied building unit, displayed in Figure 41, is located in Campi Bisenzio near Florence in Italy. This demo site is a multifamily dwelling unit built in 1984. The building is divided into four floors, with a total of 12 apartments distributed over three identical floors, and the ground floor hosting a few car parking spots, the cellars and the entrance to the building. Each floor includes 2x larger apartments (84.7 m^2 net floor area), 1x medium apartment (66.4 m^2 net floor area) and 1x smaller apartment (43.9 m^2 net floor area). The total gross heated area of the building is 972 m^2 and the total built volume 4384 m^3.

The pre-retrofit energy system is constituted by individual methane gas boilers for the production of space heating and DHW preparation. The space heating power is delivered to the heated spaces through column radiators. There is no centralized space cooling system in place, and the installation of split air conditioning unit is left to the action of single tenants. There is no heat recovery mechanical ventilation but an exhaust ventilation duct is used to extract air on-demand from toilets and kitchens. All apartments are equipped with electrical, gas and water consumption meters. The envelope includes one-pane glazing and external walls made of reinforced concrete and 11 cm of EPS for insulation. The windows are equipped with manual roller shutters.

Figure 41. Picture of the Italian demo-case of Energy Matching in Campi Bisenzio (Italy)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°768766

4.2.2 Retrofit intervention

The renovated energy system is water-based and can provide space thermal conditioning (heating and cooling) and DHW preparation by using centralized energy generators that replace the existing individual boilers. The renovated energy system is constituted of a generation plant and two heat storages and a new pipework that allows to distribute DHW and heating/cooling water to the terminals in the single apartments. A conceptual representation and a simplified layout of the energy system is shown in below Figure 42 and Figure 43.

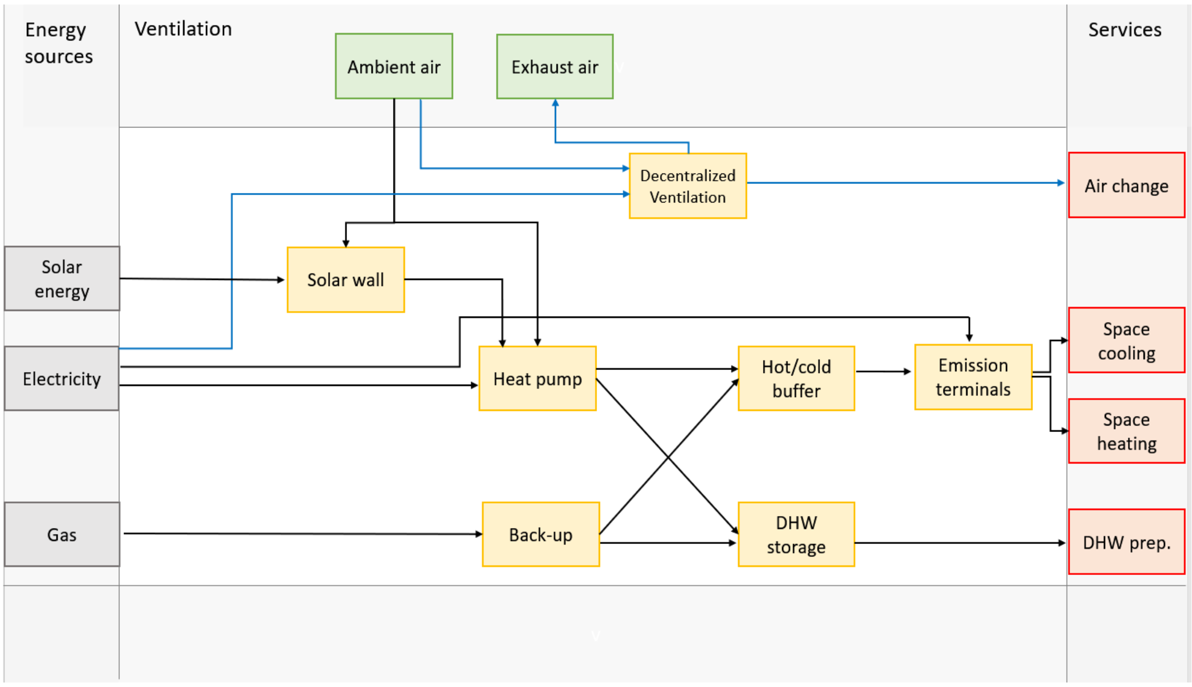


Figure 42. Conceptual representation of the renovated energy system of the Italian demo-case

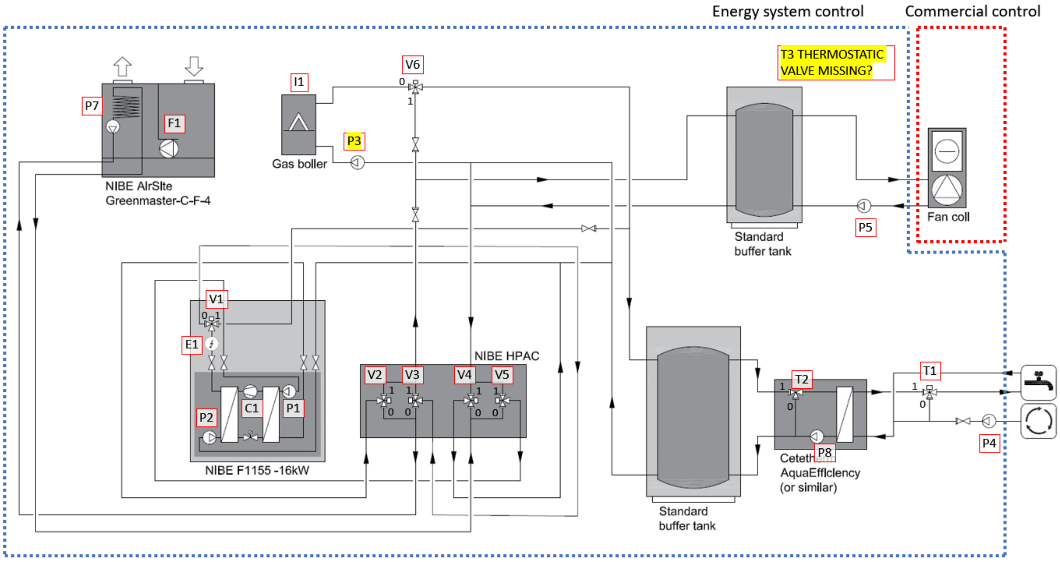


Figure 43. Simplified layout of the renovated energy system of the Italian demo-case

The energy generators are (1) a 28-kW air/water heat pump and (2) a 35-kW back-up gas boiler that is used when the heating power overmatches the capacity of the heat pump. The heat pump is exploited to generate heating or cooling power at the load side depending on the working mode. During wintertime, the air/water heat pump uses ambient air or pre-heated air coming from an air-based solar thermal collector (SolarWall) to generate heat. During summertime, ambient air is used as heat source when the of the heat pump in cooling mode, whereas pre-heated air is used for DHW production. The energy system includes two water tanks that are used to store sensible heat. The first one (named "DHW storage" in the following) is used to store heat for the preparation of DHW and is connected to both generators and to the DHW pipework. The second water tank ("buffer tank") is smaller in size and is connected to the heat pump and to the secondary water circuit used for space thermal conditioning. The buffer tank is filled with hot water during wintertime and with cold water during summertime. The transfer of heat from one storage to the other is not foreseen. The emission terminals are fan coil units installed in the single apartments that transfer thermal power from a heating/cooling water flow to an air flow rate in the single rooms.

Concerning the envelope, an improved level of thermal insulation is reached by:

- Installing an additional 12 cm thick EPS layer to the opaque section of external walls and ground floor, and 16 cm of XPS as roof insulation;
- Replacing single-pane windows with monoblocks integrating triple-pane windows and motorized blinds. In the solution that was chosen, it is possible to reach $U_{std} = 0.8\ W/m^2K$ thermal transmittance and a g-value of 0.54. Window monoblocks are also equipped with a decentralized heat recovery ventilation unit, which is powered by a BIPV panel installed on the monoblock structure.

Furthermore, the installation of a centralized PV system of the roof is foreseen to cover common electricity consumption. Table 11 summarize the overall energy concepts for the Italian demo case.

Table 11. Overall energy concepts for Italian demo case

	Intervention
1	Installation of window monoblocks with insulated glass units, automated venetian blinds, decentralized ventilation and BIPV panels
2	Replacement of existing individual boilers with centralized heating system composed of external air-water heat pump + backup (gas boiler) and transpired solar thermal collectors
3	Installation of photovoltaics on the façade/roof to cover common electricity consumption
4	Installation of thermal insulation on external walls, ground and roof

4.2.3 Preliminary evaluation of the energy demand pre- and post- retrofit

Annual energy simulations are carried out to pre-size the energy components and to assess the energy demand of the building in pre- and after- renovation states. The simulation model is illustrated in Figure 44. The results that concern the HVAC system are here discussed. Figure 45 shows the useful energy demand (i.e. the energy delivered to users and occupied spaces) of the Italian demo-building split into space heating, space cooling and DHW preparation thermal contributions. As it can be seen, the refurbishment allows to considerably reduce the space heating demand from over 80 $kWh/m^2/y$ to less than 20 $kWh/m^2/y$. This is mainly due to the addition of a thermal coat and the replacement of the single pane windows with more performing ones. With the refurbishment, a centralized heat pump and fan coil system is installed making it possible to generate and deliver cooling energy. The cooling energy demand is about 20 $kWh/m^2/y$ and is in the same range as the space heating demand. The use of automated shadings, the external shadings of trees and surrounding structures as well as the limited g-value of the windows contribute to reduce the cooling load of the building. The DHW thermal laod does not change with the refurbishment of the building and remains close to 25 kWh/m^2/y. As it can be noticed, the space heating load was about three times larger than then DHW load in the pre-renovation state, whereas they are very similar in the post-renovation status.

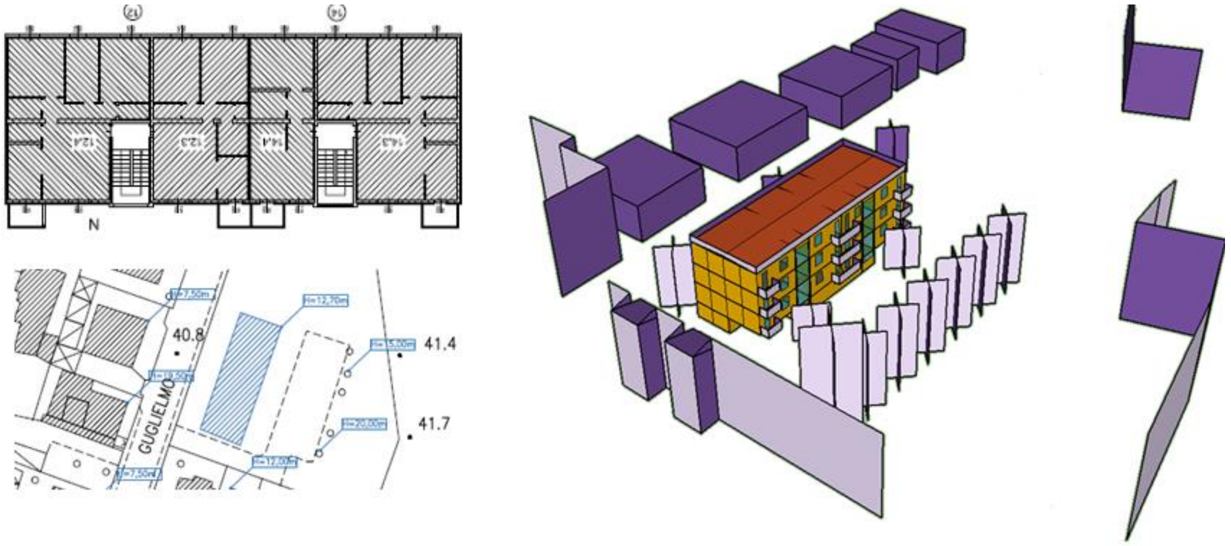


Figure 44. Blueprint and view of the studied building model for the Italian demo-case

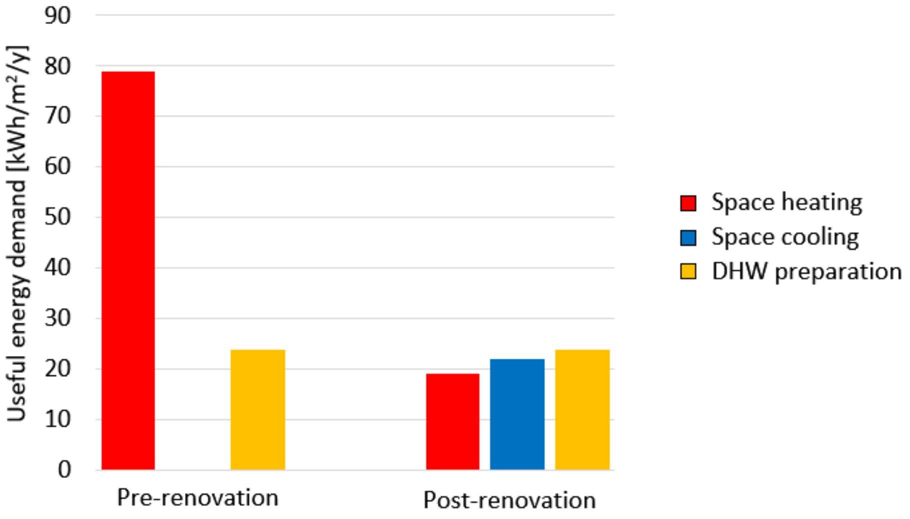


Figure 45. Useful energy demand (thermal energy) of the Italian demo-building

The monthly space heating space cooling and DHW preparation thermal loads are shown below in Figure 46 for the post-retrofit status. As it can be seen, the DHW preparation heat demand does not show significant monthly variations and slightly varies around the value of 2.0 kWh/m^2/month. On the contrary, the space heating load is concentrated during wintertime, or between November and March due to the varying climating conditions throughout the year. The total thermal heating load can indeed increases up to four times comparing the summer and winter season. The cooling load is obviously concentrated during summertime, from May to September. There are two transition months (April and October) where neither space heating nor space cooling energy demand is registered.

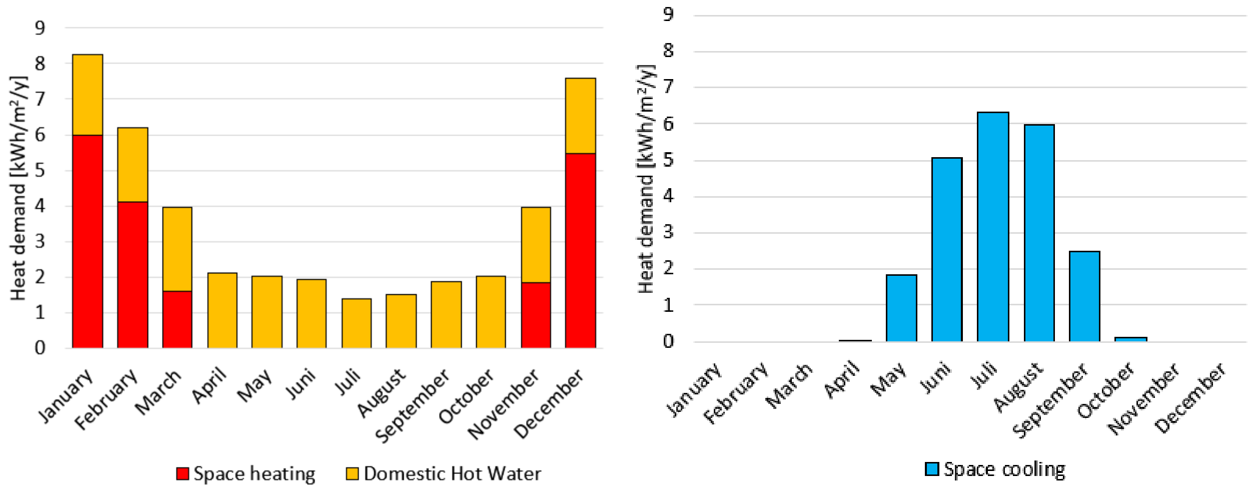


Figure 46. Monthly useful energy demand (thermal energy) of the Italian demo-building

Figure 47 shows the thermal load for space heating, space cooling and DHW preparation in the renovated state. As it can be seen, the sensible space heating and cooling thermal loads peak around 20 W/m^2, whereas the DHW preparation loads has a very high peak at almost 60 W/m^2. This is due to the fact that the DHW thermal load is mostly concentrated in a few hours of the day, with a peak during the early morning and one during the early evening, and shows large heat demands for short periods of time. In order to avoid to oversize the generators, the use of heat storages allow to better cope with the load distributing it over larger time periods. The data shown below are used (among others) to size some components of the HVAC systems.

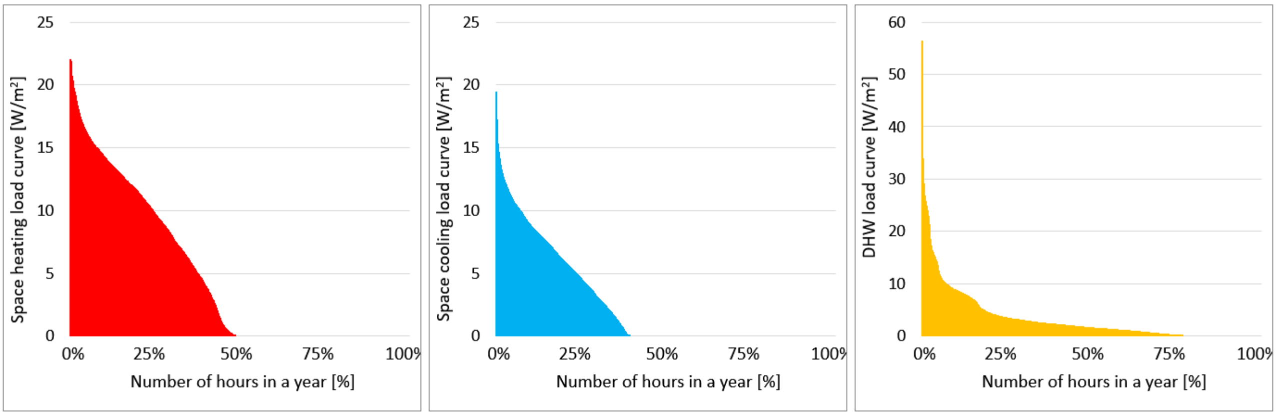


Figure 47. Thermal load of the Italian demo-building split into space heating (red), space cooling (only sensible heat) (blue) and DHW preparation (yellow)

Finally, the monthly electricity and gas demand of the post-retrofit status is shown below in Figure 48. The gas demand is connected to the use of the back-up system and can be observed only during the wintertime. The electricity demand is connected to the use of the heat pump and its ventilation coil, whereas the electricity of the decentralized ventilation units is not accounted, being such consumption already covered with the BIPV modules on the monoblocks. Furthermore, the consumption of auxiliaries (water circulators) is not included. The electricity demand of the heat pump shows a peak during winter months when it is used to produce DHW preparation and space heating energy and summer, when space cooling is needed. Local minimum values are instead found during transition months, when space conditioning is not needed.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°768766

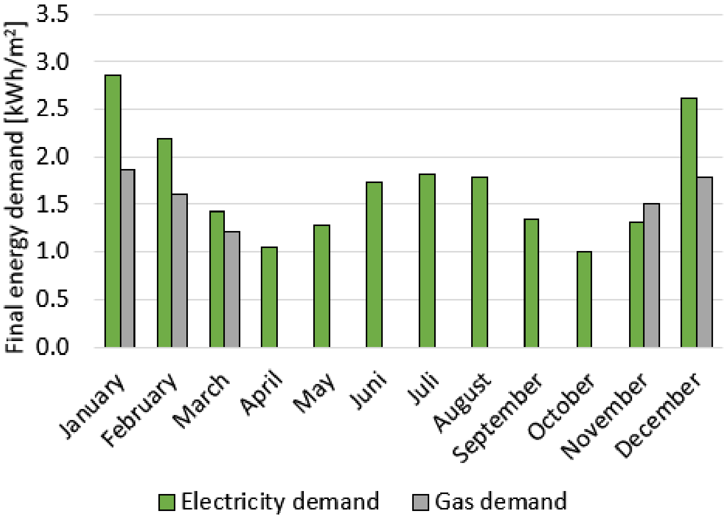


Figure 48. Monthly electricity (in green) and gas (in grey) demand of the HVAC system

4.3 French demo case

4.3.1 Demo case information

The French demo case is a building cluster located in Saint Aubin Sur Scie in the north of France. The building cluster is constituted by two multifamily dwelling units built in 1969 and retrofitted in 1988. The building cluster includes a total of 22 apartments, divided into a first building ("building A") that hosts 6 apartments split in three floors and a second building ("building B") that hosts 16 apartments split in four floors. Both buildings have a basement. The floor height is 2.5 m and the gross total area is 419 m^2 for building A and 1064 m^2 for building B. Figure 49 shows a view of the demo-site.

The pre-retrofit energy system is constituted by individual gas boilers (capacity around 23-24 kW each) to produce space heating and DHW preparation. The space heating power is delivered to the heated spaces through column radiators. There is no heat recovery mechanical ventilation but an exhaust ventilation duct is used to extract air from toilets and kitchens. The envelope includes double-pane glazing (4/16/4 with air gap) and external walls made of bricks and a glass wool insulation layer (7 cm). The external walls of the fourth floor also integrate an additional 8 cm thick layer of EPS. The windows are equipped with manual roller shutters and trickle vents to allow the exchange of air with the exterior.

Figure 49. Picture of the French demo-case (Building A) of Energy Matching in Saint Aubin Sur Scie (France)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°768766

4.3.2 Retrofit intervention

The renovated energy system is water-based and can provide space thermal conditioning (heating only) and DHW preparation. The renovated energy system is constituted of a generation plant and two heat storages serving both buildings. A new pipework is built to distribute heating/cooling water to the terminals in the single apartments. A conceptual representation and a simplified layout of the energy system is shown in Figure 50. The energy generators are (1) a 16-kW exhaust air heat pump and (2) a gas boiler as back-up. The heat pump is equipped with inverter and can work at partial loads. In the studied configuration, only the generation of heating power is foreseen, differently from the system in the Italian demo-case where cooling energy was also produced during summertime. During the year, the heat pump works then in space heating or DHW preparation modes depending on the demand. Exhaust air is extracted from the dwellings using centralized extractors installed on the top of the stairways (one in building A and two in building B) and such air flow is used as heat source for the heat pump. The air extraction system integrates indeed a heat exchanger that is connected to the evaporator of the heat pump. As the extracted air is a limited resource, unlike ambient air, the heat pump was sized in this case based on this limit, rather on the thermal load and coverage factors as for the Italian demo-case.

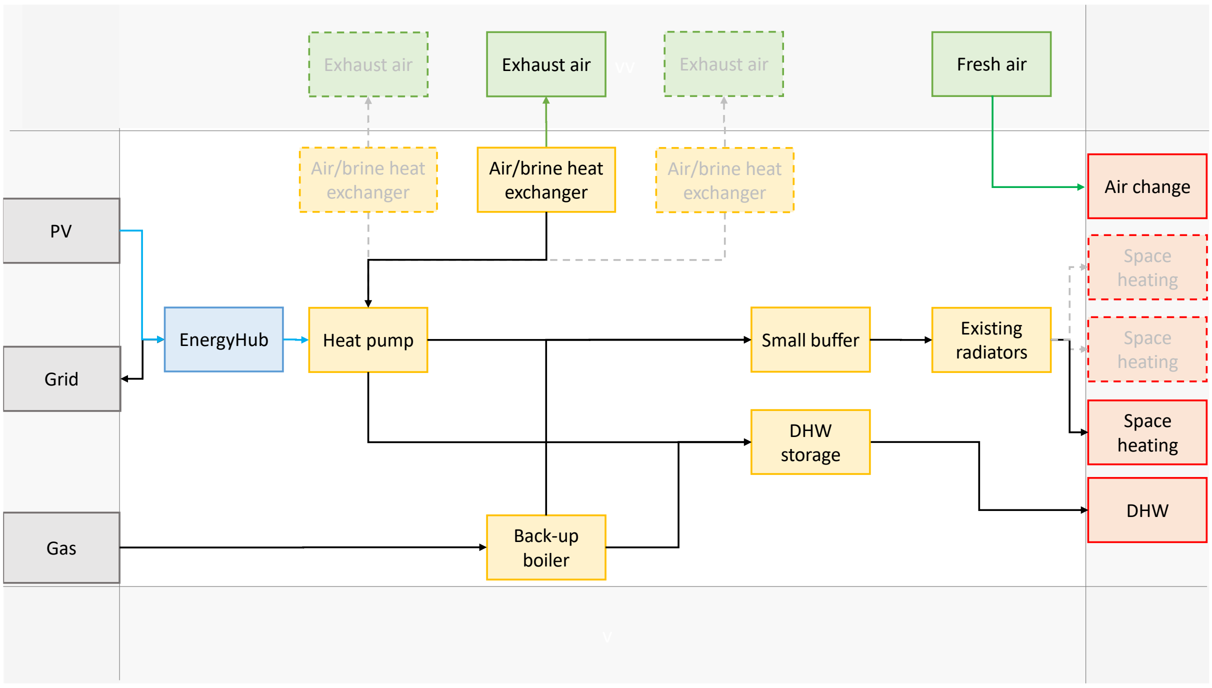


Figure 50. Conceptual representation of the renovated energy system of the French demo-case

The energy system includes two water tanks that are used to store sensible heat. The first one is used to store heat for the preparation of DHW and is connected to both generators and to the DHW pipework. The second water tank is smaller in size and is connected to the heat pump and to the secondary water circuit used for space thermal conditioning. The transfer of heat from one storage to the other is not foreseen. The emission terminals are the existing column radiators installed in the dwellings, which the demo-owner did not to plan to change during this intervention. A preliminary study on temperature levels and thermal power loads in the single dwellings was carried out, leading to the elaboration of a suitable hydraulic scheme that allows to top up the heat production of the heat pump with the gas boiler. In this way, it is possible to generate high temperature water during the coldest days of the year and use the existing radiators as emission terminals.

Concerning the envelope, an improved level of thermal insulation is reached by:

- Installing an additional insulation layers to the external walls (R = 3.68 m^2K/W), ground floor (R = 2.8 m^2K/W) and roof (3.68 m^2K/W);

- Replacing double-pane windows with window monoblocks integrating triple-pane windows and motorized blinds. In the solution that was chosen, it is possible to reach U_{std} = 0.8 W/m2K thermal transmittance and a g-value of 0.54. The window monoblocks are equipped with trickle vents that allow to control the incoming air flow from the exterior in case of high wind pressure. During normal operation, fresh air is instead moved to the interior by the pressure depression caused by the mechanical air extractors.

The installation of a centralized PV system of the roof and facade is foreseen to cover a share of the common electricity consumption. Table 12 summarizes the overall energy concepts for the French demo case.

Table 12. Overall energy concepts for French demo case

	Intervention
1	Installation of window monoblocks with trickle vents
2	Replacement of existing individual boilers with centralized heating system composed of exhaust air heat pump, back-up gas boiler. Existing terminals (column radiators are kept)
3	Installation of PV on the façade/roof to cover common electricity consumption
4	Installation of thermal insulation on external walls, ground and roof

4.3.3 Preliminary evaluation of the energy demand pre- and post- retrofit

Annual energy simulations were carried out to pre-size the energy components and to assess the energy demand of the building in pre- and after- renovation state. The simulation model is displayed in Figure 51. The results of the dynamic energy simulations were only one of the inputs needed by the specialists to design and size the energy system, as static calculations, the conformity with local regulations and considerations that go beyond the energy aspect are taken into account to find a suitable design of the HVAC system. Figure 52 shows the useful energy demand of the French demo-building split into space heating and DHW preparation in the pre- and after- renovation states. As already discussed, space cooling is instead not possible with the designed HVAC layout. The addition of the thermal coat and the replacement of the windows allows to significantly reduce the space heating demand, which decreases from over 100 kWh/m^2/y to less than 50 kWh/m^2/y. Such reduction is however not extreme, due to the fact that the performance of the building envelope was already not excessively poor (the buildings were already retrofitted in 1988). In addition, the use of an exhaust air ventilation system with trickle vents (in the pre- and post- renovation stages) makes the ventilation heat losses inavoidable. The thermal load connected to DHW preparation (27 kWh/m^2/y) does not change with the retrofit of the building, as it is expression of the energy uses of the occupants. It is observed that the space heating energy load is about 4x times higher than the DHW preparation load in the prerenovation stage and becomes less than the double after renovation.

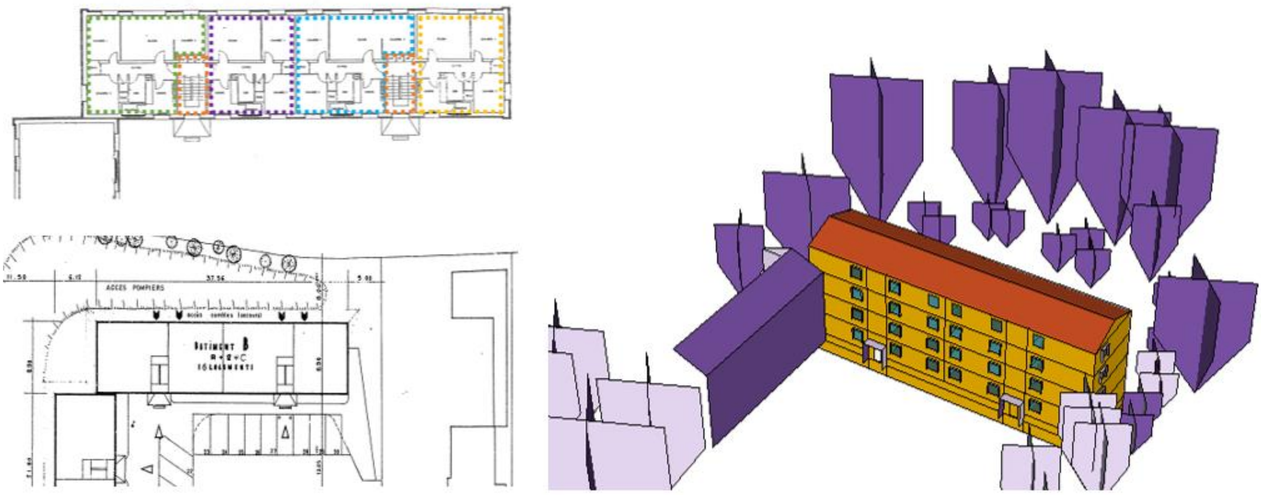


Figure 51. Blueprint and view of the studied building model for the French demo-case, Building B

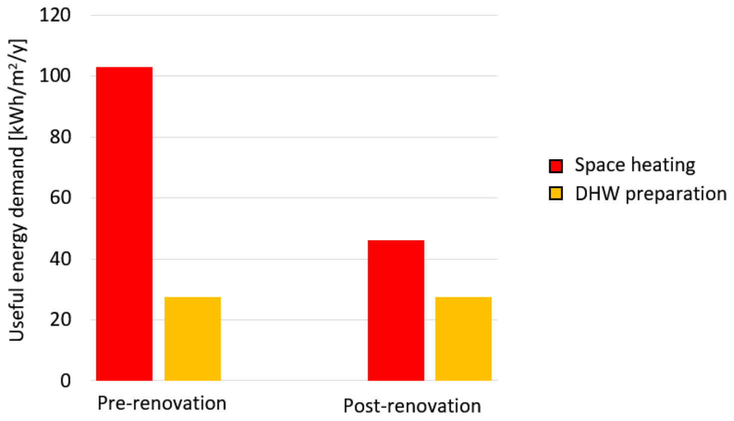


Figure 52. Useful energy demand (thermal energy) of the French demo-building, Building A+B

The monthly space heating and DHW preparation thermal loads are shown below in Figure 53 for the post-retrofit status. The DHW preparation heat demand does not show significant monthly variations and slightly varies around the value of 2.3 kWh/m^2/month. On the contrary, the space heating load is concentrated during wintertime, or between October and May due to the varying climating conditions throughout the year. It is observed that the harsher climate of Saint Aubin Sur Scie translated to a longer heating season in comparison to the Italian demo-case.

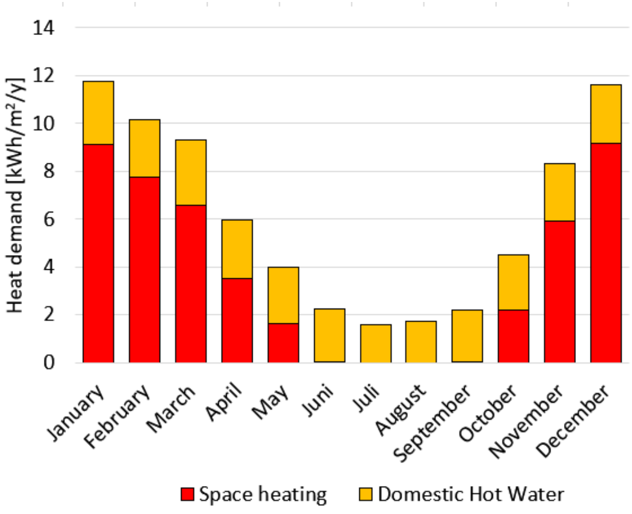


Figure 53. Monthly useful energy demand (thermal energy) of the French demo-building after retrofit, Building A+B

The final energy demand (bought energy) after the renovation is shown in Figure 54. The results are for the system with an extra store of 0.75 m^3 for storing PV excess in the form of heat and for a gas boiler efficiency of 90%, while the electricity demand is that bought from the grid. In addition to this, 2200 kWh PV electricity can be exported to the grid (1.5 $kWh/m^2 \cdot year$). Compared to the Italian demo case, the electricity demand is similar in winter, but significantly lower in summer due to the fact that there is no cooling demand. The gas demand is much higher due to the higher heating loads and the fact that the heat pump has a limited capacity due coupled to the ventilation rate.

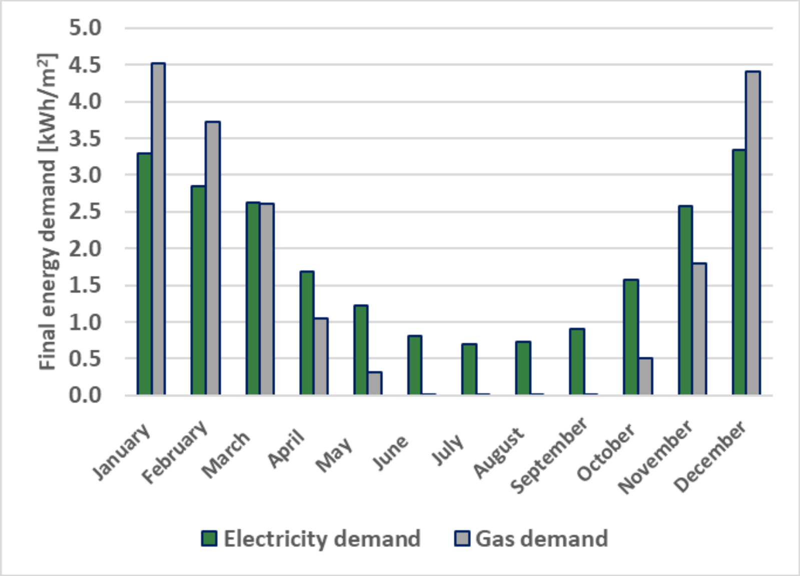


Figure 54. Monthly electricity and gas demand of the HVAC system for the French demo-building

4.4 EnergyMatching tool for optimized design: a case study in Swedish demo

4.4.1 Optimized design process

Based on the preliminary design in section 4.1, it is possible to further optimize the energy designs in the Swedish demo case, using the EnergyMatching tool (ER2) from WP2. The energy demand, as the main input to EnergyMatching tool, has been estimated in section 4.1. The EV load is generated by using the Grahn-Munkhammar model [10]. The result of the optimization process strongly depends on the demand, but the demand itself is influenced by the excess PV electricity (the excess PV power will be used by the heat pump), which is in turn influenced by the result of the optimization. The optimal PV system is generally characterized by some hours of over-production along the year: if this over-production is used to heat a thermal storage, the energy transfer to the local grid is reduced. The reduction of over-production would cause an increase in the optimal dimension of the PV system because it will effectively be an increase in electric demand, this causes a positive feedback loop (see Figure 55) until convergence (i.e. when the average temperature of the extra storage is high enough to send electricity to the grid anyway). The optimal configuration of the PV system is shown in terms of capacity on the different roofs and façades in the building cluster, and different optimal PV configuration will be shown following an increasing order in terms of demand covered.

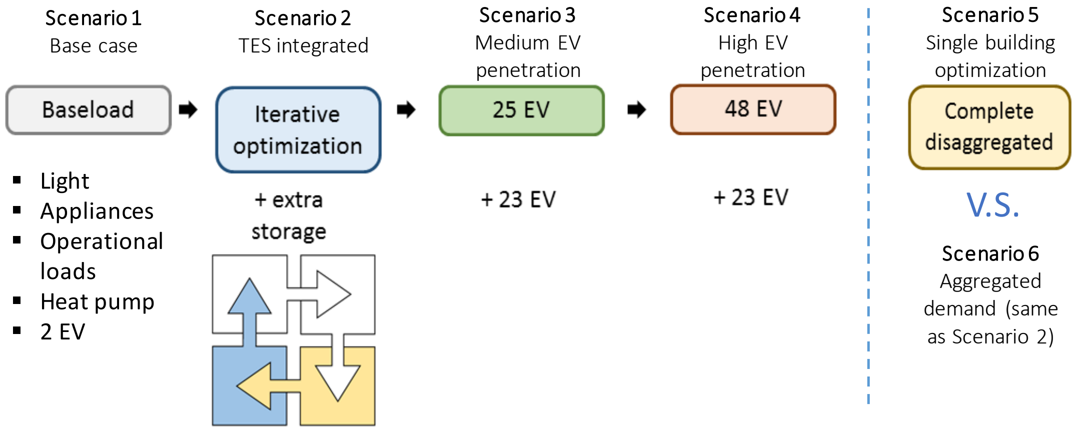


Figure 55. Steps to produce the five optimal configurations analyzed in the study: the baseload consists of public and private lights and appliances, common operational loads, heat pump demand, domestic hot water and two EVs. The tone of color used in the chart is reported also in the 3D representation of the different configurations

Table 13. Configurations of systems and demands in each scenario

ID	Scenarios	Energy sharing	Thermal energy storage	EV number
1	Base case	Yes	No	2
2	TES integrated	Yes	Yes	2
3	Medium EV penetration	Yes	Yes	25
4	High EV penetration	Yes	Yes	48
5	Single building optimization	No	No	2
6	Aggregated demand (same as Scenario 2)	Yes	Yes	2

4.4.2 Design results of the coupled system for the base load scenario

The first run of optimization is the one that includes the smallest possible electric demand, in this scenario no extra thermal storage for the excess PV electricity is included and the number of EV is only the minimum of two in the whole cluster of buildings. Figure 56 (a) shows the optimal configuration of PV modules over the roof and façade of the cluster. The screenshot on Figure 56 (b) shows in color-coded disks the annual cumulative irradiation over the different façades. The southern slope of the roof is clearly more irradiated than the rest of the surfaces made available for a PV system averaging just below 1,200 kWh/m^{2}year. The east and west slopes are a bit better irradiated than the south façades, despite this, a significant portion of the system is installed on the southern façade while much of the roof is still available. The southern façade turns out interesting for the optimization algorithm as it enjoys a more homogeneous irradiation throughout the year, during the winter season the solar angle is closer to the horizontal than the vertical and irradiates the southern façade more than the roof.

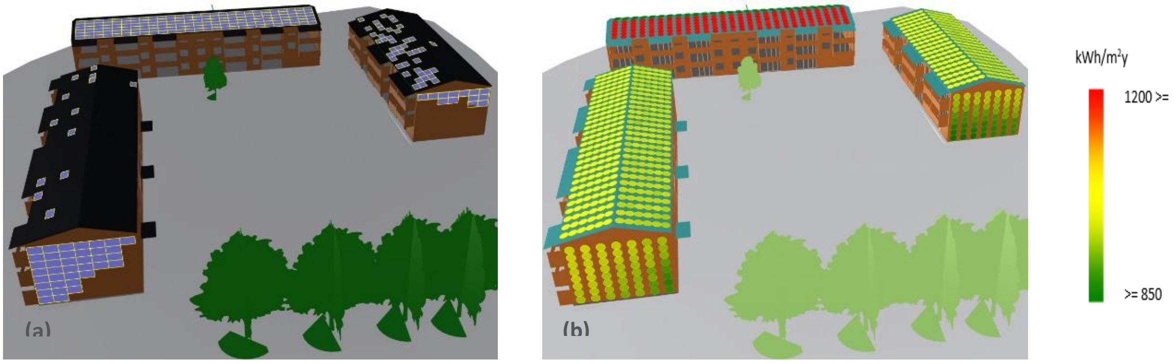


Figure 56. EnergyMatching tool optimization result in Swedish demo case: (a) The optimal configuration for the baseline case; (b) Color-coded depiction of the annual cumulative irradiation

Table 14 shows the main KPIs reached by the optimal system for the baseload scenario. Overall, the collection of KPIs can be considered satisfying, in fact it shows that it is possible to cover (contemporaneously to the production) ca. 20% of the electric demand of the cluster while retaining an excellent level of self-consumption of ca. 77%. Despite being at high latitude, the system reaches pleasant results. The reason for this might be the aggregation of the demand. A single-family house has a demand profile that is really hard to match for a PV system lacking storage (or with minor storage), this is due to the strong variability of the load that is characterized by an extremely low baseline and huge "spikes" or "peaks".

Table 14. Main KPIs reached by the optimal system in Swedish demo case

	KPI	Value
	Installed capacity [kWp]	65.5
	Installed storage capacity [kWh]	0.3
	Installed area[m²]	376.5
	Capacity of electric storage [kWh]	0.3
	System cost [€]	93,017
	Expected self-consumed-LCOE [€ cent /kWh]	17.9
	Expected LCOE [€ cent /kWh]	14.5
	Self-consumption [%]	76.9

4.4.3 Summary of sensitivity analysis results in other scenarios

The overall energy benefits from applying the retrofitting intervention are that heat pump covers 56% heat demand, and the bought energy is reduced by 42%. The integration of thermal energy storage, together with suitable control for storing heat using PV excess production, will lead to increase in the optimal capacity of PV systems, as charging of thermal energy storage will increase electrical load. Due to an increased match between the electrical demand and power generation, the integration of thermal energy storage is beneficial for increasing renewable energy self-consumption, i.e. self-consumption increased from 77% to 79.4%. The integration of thermal energy storage does not affect levelized cost of electricity too much, as both the power generation and the costs increase.

The integration of electric vehicles will lead to increase in the optimal capacity of PV systems that maximizes the self-consumption, in this case study the self-consumption rate increased from 79.4% to 80.9% when EV number increased from 2 to 48. Meanwhile, due to the increased self-consumption, the levelized cost for the self-consumed electricity will be reduced slightly.

Aggregating the building demand and supply by enable energy sharing will lead to increase in the optimal capacity of PV systems that maximizes the self-consumption rate, since energy sharing makes the PV system more versatile, and thus the whole cluster is more efficient at consuming the electricity produced on-site. The self-consumption will be reduced (i.e. 7.8% decrease), but this will be compensated by a dramatic increase in the self-sufficiency (i.e. 23.8% increase). The levelized cost of electricity is not affected by aggregating the building demand and supply [7].

4.5 Summary of energy-saving benefits in three demo cases

The system concept solutions for all the three demonstration sites have been developed iteratively together with partners in Task 2.4 and Task 6.2, and the input from the technology providers in WP3 and WP4. The thermal and electricity load profiles of the demo cases have been initially simulated and calibrated. The electricity load profiles are further delivered as the input for the generic simulation work in Task 2.4. Iterated discussions have been conducted among project partners on overall system concepts, as well as on boundary conditions and evaluation metrics.

Table 15 summarizes the energy-saving benefits in the three demo cases, in the case of evaluations by simulation approach.

Table 15. Summary of energy-saving benefits in three demo cases

Demo	Main energy benefits using Energy Matching concepts	
SE	Pre-retrofit	• Space heating demand: 109.8 kWh/m^2/y • DHW heating demand: 26.6 kWh/m^2/y
	Post-retrofit	• Space heating and DHW demands are the same as pre-retrofit • Heat pump covers 56% demand of space heating and DHW • Bought energy is reduced by 42%
IT	Pre-retrofit	• Space heating demand: 80 kWh/m^2/y • DHW heating demand: 23.8 kWh/m^2/y • Space cooling demand (sensible only): 0 kWh/m^2/y (no cooing system)
	Post-retrofit	• Space heating demand: 18 kWh/m^2/y • DHW heating demand: 23.8 kWh/m^2/y

		Space cooling demand (sensible only): 17 kWh/m^2/y
FR	Pre-retrofit	Space heating demand: 100 kWh/m^2/y DHW heating demand: 27 kWh/m^2/y
	Post-retrofit	Space heating demand: 50 kWh/m^2/y DHW heating demand: 27 kWh/m^2/y

5. Conclusions

In WP4, a number of energy concepts has been studied on the basis of the technologies of the project. Several considerations have been made about the possible way to couple the single components and benefits and risks have been highlighted. Moreover, the preliminary designs in three demo cases are made and evaluated.

With regard to the three demo-cases of the Energy Matching project:

- In the Swedish demo-case, a centralized exhaust air heat pump system for multiple building will be installed (Section 2.2). In addition, a district DC grid (Section 3.3), consisting of EnergyHub (section 1.4) will be put in place. The advanced control for PV driven heat pump (section 3.2) will be applied for hot water storage with excess PV electricity.
- In the Italian demo-case, a solar assisted air-source heat pump (Section 2.1) will be installed in combination with solar window packages (Section 3.1) and SolarWall (section 1.2);
- In the French demo-case, a centralized exhaust air heat pump system for multiple buildings will be installed (Section 2.2). Besides, window monoblocks with trickle vents (section 1.5) are considered.

In all three demos, the installation of lightweight BIPV is foreseen to cover part of the electric load of the buildings and EVs (section 3.3 & 3.4), with the possibility to implement advanced controls coupling PV electrical production and heat pump (Section 3.1 & 3.2).

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